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United States Department of Energy

Office of Energy Research
Office of Health and Environmental Research
Carbon Dioxide Research Program

Carbon Dioxide and Climate: Summaries of Research in FY 1991

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FOREWORD

Global climate change has become almost a household word these days. Every unusual weather event, even if fully explainable by the natural variability of climate, is attributed to increasing carbon dioxide concentrations and other emissions from man's activities. An emotional public debate is fueling the race for more-stringent emission controls, including international agreements and legislative fixes.

The rise in environmental consciousness is a positive sign of mankind's shift from base ambitions and parochial interests to concerns regarding the global habitability of our planet. Historical changes in the world's political landscape are under way following the collapse of communism. They will help translate the rise in environmental consciousness into substantive action plans that address many of the serious environmental problems resulting from decades of unchecked industrial activities in certain parts of the world.

Global climate change is a serious environmental concern, and the U.S. has developed "An Action Agenda" to deal with it. At the heart of the U.S. effort is the U.S. Global Change Research Program (USGCRP), which has been developed by the Committee on Earth and Environmental Sciences (CEES) of the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET). The USGCRP will provide the scientific basis for sound policy making on the climate-change issue. The DOE contribution to the USGCRP is the Carbon Dioxide Research Program, which now places particular emphasis on the rapid improvement of the capability to predict global and regional climate change.

DOE's Carbon Dioxide Research Program has been addressing the carbon dioxide-climate change connection for more than twelve years and has provided a solid scientific foundation for the USGCRP. The expansion of the DOE effort reflects the increased attention that the Department has placed on the issue and is reflected in the National Energy Strategy (NES) that was released in 1991.

This Program Summary describes projects funded by the Carbon Dioxide Research Program during FY 1991 and gives a brief overview of objectives, organizations, and accomplishments. The contributions from all the Program's participating scientists are greatly appreciated.

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

PREFACE

This document describes the activities and products of the Carbon Dioxide Research Program (CDRP) in Fiscal Year (FY) 1991. The report is organized in four main sections.

SECTION	DESCRIPTION
Introduction	▸ Describes overall CO_2 issues
	▸ Ties CO_2 issues to the research approach, program goals, and objectives
	▸ Relates each specific research area to the overall goals of the program
	▸ Shows the level of effort
Research Areas and Project Descriptions	▸ Describe the scientific questions in each research area
	▸ Provide descriptions of individual research projects
	▸ List the expected product for each project
	▸ Show the research approach or method used in each project
	▸ Provide results to date when applicable
Appendix	▸ Provides locator information on principal investigators and their research institutions for the overall report
Indexes	▸ Provide indexes of keywords, principal investigators, and research institutions for easy reference

Questions concerning the Carbon Dioxide Research Program or specific projects may be addressed to the Environmental Sciences Division, U.S. Department of Energy, ER-74, Washington, DC, 20585. The Program's telephone number is (301) 903-3281.

INTRODUCTION

The Environmental Sciences Division of the Office of Health and Environmental Research, Office of Energy Research (Figure 1) supports a **Carbon Dioxide Research Program** to determine the scientific linkage between the rise of greenhouse gases in the atmosphere, especially carbon dioxide, and climate and vegetation change.

One facet is the **Core CO_2 Program** (Figure 2), a pioneering program that DOE established more than 10 years ago to understand and predict the ways that fossil-fuel burning could affect atmospheric CO_2 concentration, global climate, and the Earth's biosphere.

CORE CO_2 PROGRAM

Global Carbon Cycle. Understanding global carbon dynamics to predict future atmospheric CO_2 concentration is the main objective. This effort involves research on sources, sinks, and biogeochemical processes that control the atmospheric CO_2 concentration, including measurements of carbon and physical processes in oceans related to climate. Data acquisition and modeling the CO_2 exchanges among the atmosphere, ocean, and terrestrial ecosystems have been emphasized.

Climate Detection and Models of Climate Change. This research studies the climatic interdependence of atmosphere, ocean, biosphere, and cryosphere. The objective is to understand the climate system to determine if global climate is indeed changing. A key element is the diagnostic intercomparison of climate models for evaluating the role of clouds and the regional/interannual climate sensitivity to greenhouse gases. Tested climate models are then used to determine climate sensitivity to the changing concentrations of greenhouse gases.

Vegetation Research. Experimental and modeling studies on plant physiology (including photosynthesis, transpiration, and respiration) and field-scale effects on vegetation are conducted to determine the direct effects of CO_2 and different climate conditions on plants. Basic processes for sequestering carbon on land are evaluated. The opportunity for enhancing CO_2 fixation through advances in biotechnology is a candidate research topic.

Resource Analysis. Ways that climate and vegetation change might impact health and resource sectors (such as hydrology, ecosystems, agriculture, shorelines and fisheries) are examined. One study employs historical climate variation along with the contemporary rise of CO_2 as forcings to determine the sensitivity of regional change in agriculture, water resources, forestry, transportation, etc.

Information and Integration. Global research on atmospheric CO_2 and climate generate vast quantities of data that require systematic management and information exchange. The objective of this effort is to provide mechanisms through which scientific information can be obtained, evaluated, and subjected to quality-control procedures. This function is carried out by the Carbon Dioxide Information Analysis Center, Oak Ridge, Tenn., which fosters exchange of data among scientists and other users.

EXPANDED PROGRAM

A second facet of carbon dioxide research is the **Expanded Program.** Prompted by the growing

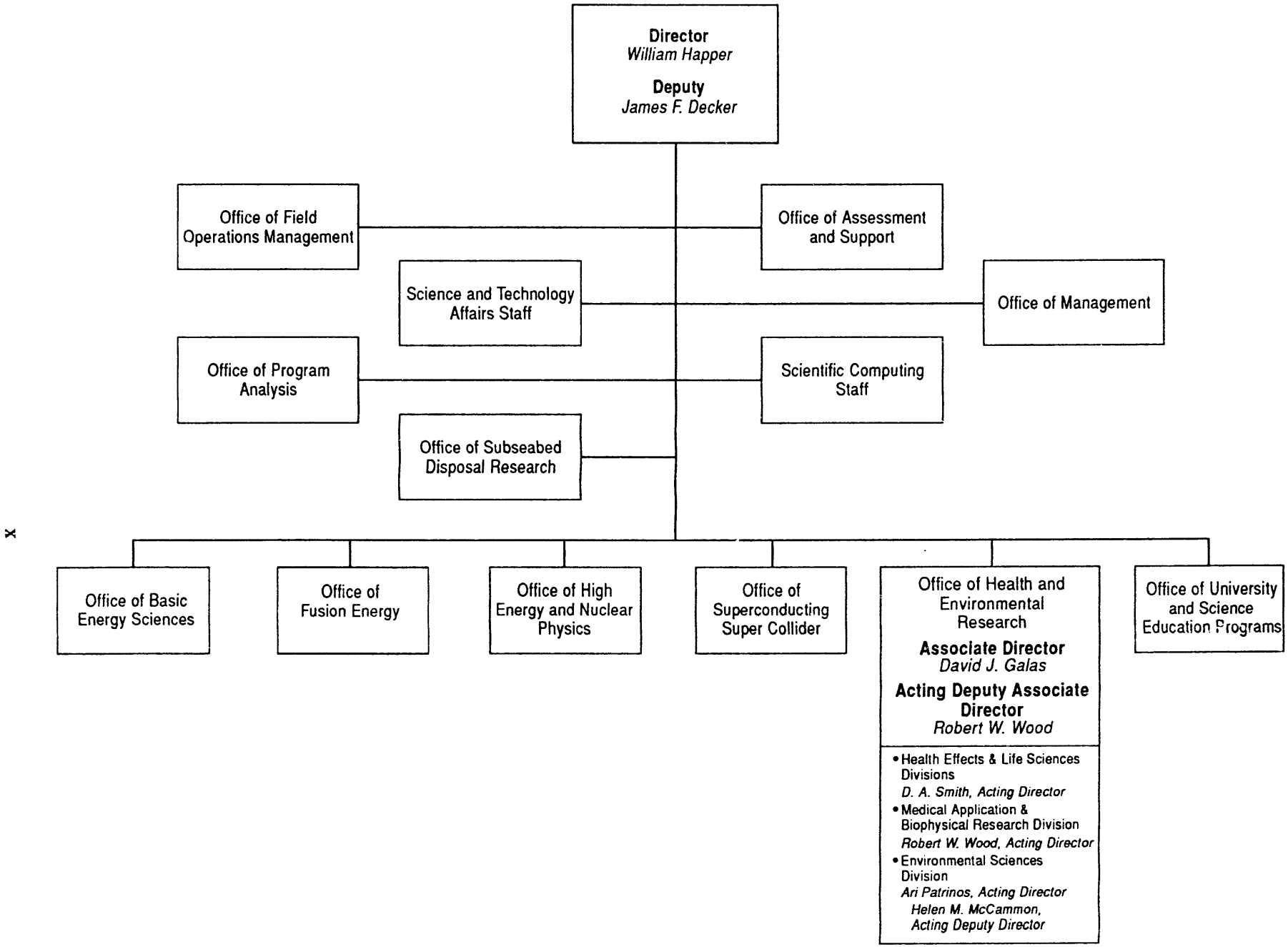

Fig. 1. Organization of DOE's Office of Energy Research.

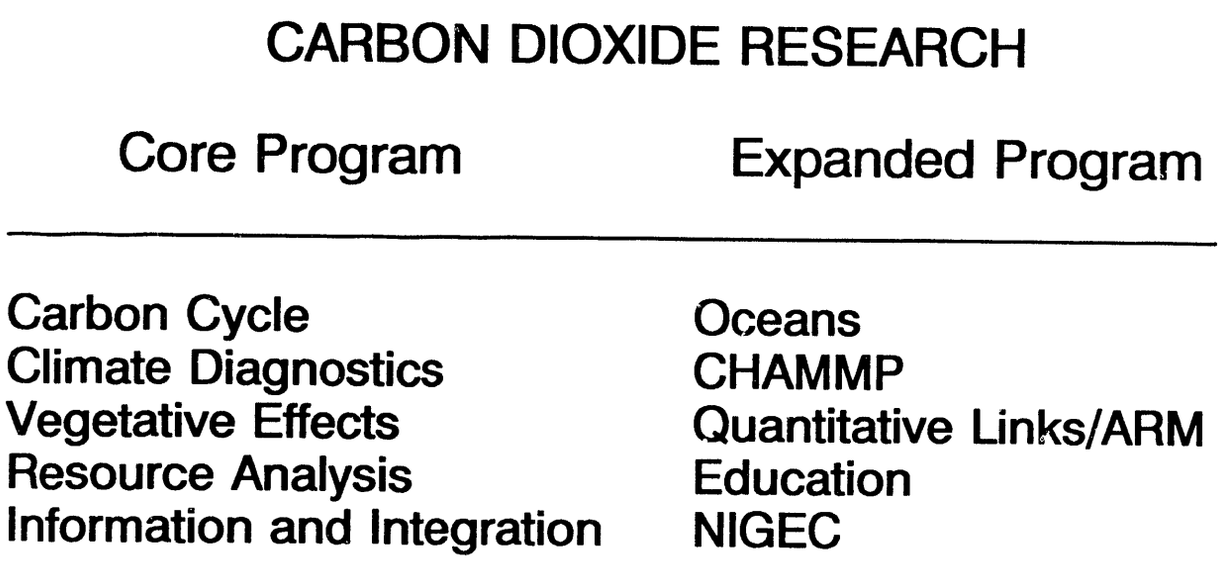

Fig. 2. Breakdown of the Carbon Dioxide Research Program Showing the Core Program and the Newer Expanded-Program Components.

concern regarding climate change, DOE has launched several initiatives.

The objective of the **Quantitative Links** initiative is to quantify the expected change in climate that may result from an increase in the atmospheric concentrations of CO_2 and other greenhouse gases. This effort includes a broad range of research on the linkages between changes in atmospheric composition and temperature.

An important element of the quantitative-link research is the **Atmospheric Radiation Measurement (ARM) Program**, which examines climate feedbacks and energy fluxes of the coupled land-atmosphere-ocean system. The objective is to quantitatively describe the radiation balance from the surface of the Earth to the top of the atmosphere and to determine the atmospheric characteristics responsible for this balance. A related objective is to use ARM measurements to understand cloud formation and clouds' proper representation in climate models. The ARM data will provide the testbed for the process models representing the cloud-climate feedbacks in the present general-circulation models (GCMs) as well as in the future climate-change-prediction models of regional-scale resolution.

The objective of the **Computer Hardware, Advanced Mathematics and Model Physics (CHAMMP) Program** is to accelerate and improve prediction of the future response of global and regional climates to the increasing atmospheric concentrations of carbon dioxide and other greenhouse gases. This task will require advanced climate models that are capable of much longer and more detailed simulations and that incorporate significant improvements in their representation of the physics and chemistry of the climate system. Developing an Advanced Climate Model (ACM) with such capabilities will require use of computers capable of increasing throughput by a factor of at least 10,000, mathematical formulations and software that utilize the extensive parallelism of the emerging generations of computers, and improved algorithms that have been more thoroughly verified with more-comprehensive sets of field observations.

The expanded program also includes an **Ocean Research Initiative**, the initial objectives of which are to conduct a global survey of carbon dioxide in the ocean and to improve the ocean-circulation models used for climate research. This research involves laboratory and field

measurements as well as modeling studies to understand oceanic mixing and transport processes, carbon cycling, and the storage and exchange of heat and carbon between the ocean and the atmosphere. In related research, advanced low-power sensors are being developed for measuring physical, optical, and chemical properties of the ocean to provide sea-truth for satellite observations and data from remote regions for verification of ocean models.

Strong Congressional interest dictated the creation of the **National Institute for Global Environmental Change** (NIGEC). The Institute is composed of a national center at the University of California at Davis and four regional centers at Harvard University, Tulane University, Indiana University, and the University of California system. NIGEC supports both the research goals of the Carbon Dioxide Research Program as well as analyses for the DOE Office of Policy, Planning, and Analysis. Among the NIGEC tasks are the development of an early warning system for energy-related environmental risks and public education programs on global change. The four centers will develop research thrusts with individual regional characteristics.

A new dimension of the DOE effort is the **Global Change Educational Initiative.** The need to train the next generation of scientists to deal with global-change problems provides the impetus of a comprehensive educational program involving fellowships at the graduate and postgraduate levels as well as the development of K-12 curricula with global-change themes.

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 government agencies. The distribution of research funds to types of research institutions by fiscal year is presented in Figure 3.

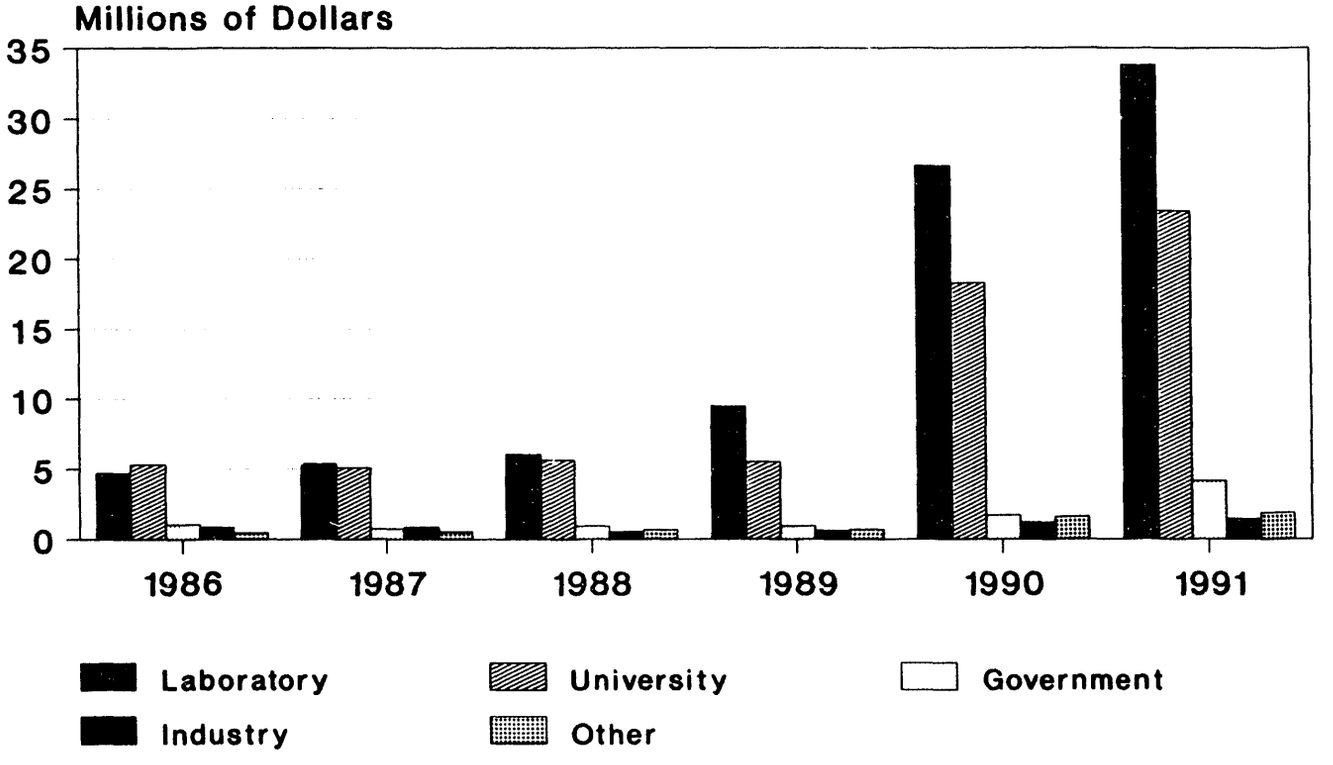

Fig. 3. Carbon Dioxide Budget History by Type of Institution.

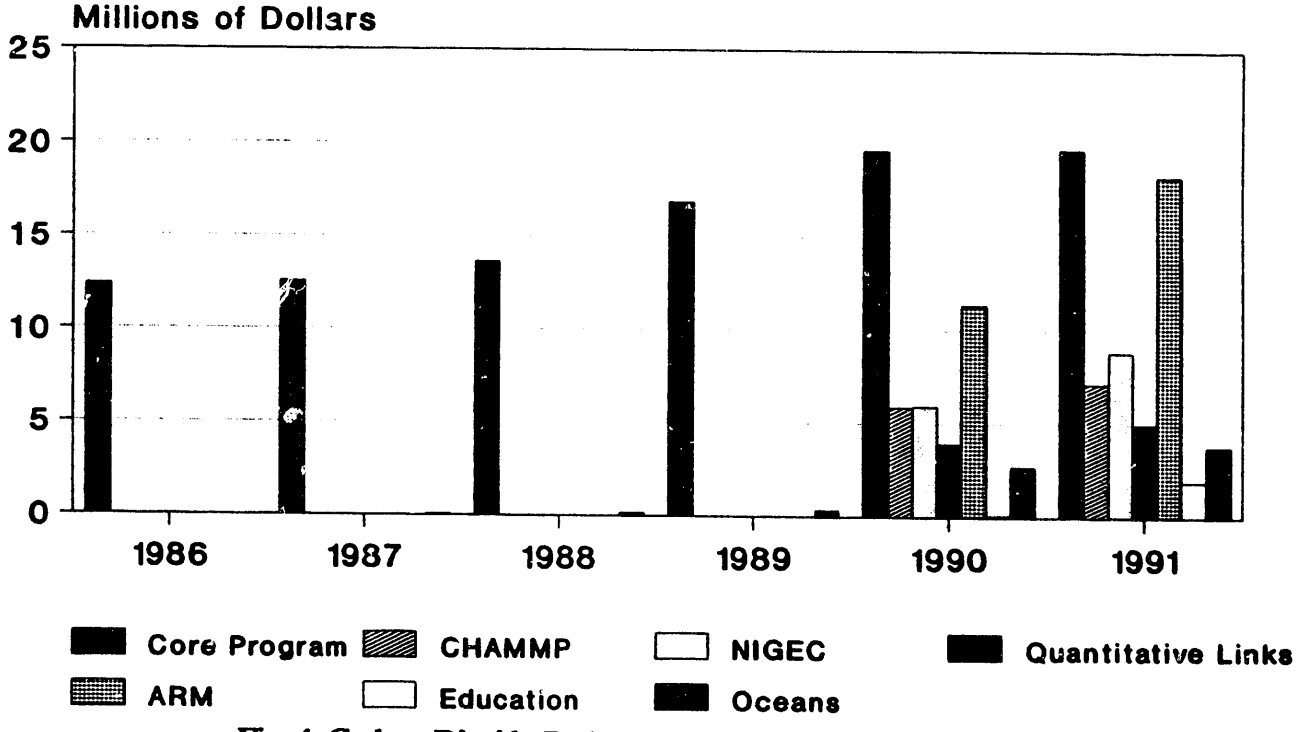

Fig. 4. Carbon Dioxide Budget History by Research Category.

LEVEL OF EFFORT

Research sponsored by the Carbon Dioxide Research Program has increased steadily since its beginning in FY 1978 when $1,479,000 was made available for program development and research. By FY 1991, the budget reached $64,407,000. The distribution of research funds to research areas by fiscal year is presented in Figure 4.

ORGANIZATION OF THE PROGRAM SUMMARY

All carbon dioxide-climate projects funded by DOE under annual contracts in FY 1991 are described in this report. Each description contains the project's title; the name(s) of the principal investigator(s); the institution(s) conducting the projects; a three-year funding history (in thousands of dollars); the contract period for which the current funding applies; and the project's objectives, products, approach, and results to date (for most projects older than one year).

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

This document has been indexed to aid the reader in locating research topics, participants, and research institutions in the text. To that end, comprehensive subject, principal-investigator, and institution indexes to the research summaries are provided at the end of the text. The subject index also covers the Introduction and chapter texts in addition to the research summaries. An Appendix gives the addresses of the participants in the main program.

GLOBAL CARBON RESEARCH

Global carbon research provides the scientific underpinnings for predicting future concentrations of CO_2 in the atmosphere. The research addresses natural systems that govern the abundance of CO_2 in the atmosphere, including the role of the oceans and terrestrial ecosystems in determining exchanges of CO_2 with the atmosphere. In addition, carbon cycle research compiles information about technology, economics, geology, and other factors required for estimating emissions of CO_2 and other radiatively important gases (RIGs).

Significant progress has been made in the past decade. 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 CO_2 emissions; estimated uncertainty surrounding future global fossil-fuel CO_2 emissions; examined the components of the ocean carbon cycle and carbon reservoirs; and estimated fluxes between the terrestrial biosphere and the atmosphere and integrated components of the carbon cycle into global models.

Despite a decade of progress, major uncertainties remain about what happens to the CO_2 generated from the burning of fossil fuels. An inability to balance the global carbon budget affects the accuracy of predictions of future atmospheric CO_2 concentrations. Moreover, the uncertainties seriously limit the ability to quantify the effectiveness of possible actions that could modify the natural carbon cycle (i.e., reforestation or enhanced carbon fixation in terrestrial and marine ecosystems) and possibly slow the rise of atmospheric CO_2.

Research Objectives. The current program is designed to take the next step beyond the current inventory of our knowledge of the carbon cycle. It aims at increasing our knowledge and understanding of the carbon cycle in order to predict change of atmospheric CO_2 from energy emissions. Specific objectives are to understand the processes of the carbon cycle, to document energy emissions of CO_2, to evaluate source–sink mechanisms for atmospheric CO_2, and to develop reliable models for projecting atmospheric concentrations of CO_2.

Research Questions. In the Carbon Cycle area:

- 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?

- What are the significant sources or sinks for carbon that must be considered?

In the Energy area:

- What are the scientific, technological, economic, and geologic data needed for estimating emissions of CO_2 and other RIGs from energy activities?

And

- How can the scientific information be used to evaluate decisions about emissions trading?

Program Manager
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Environmental Sciences Division
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Washington, DC 20585
(301) 903-4951

Research Summaries

THE EFFECTS OF CHANGING LAND USE ON CARBON AND NITROGEN IN MID-LATITUDE NORTH AMERICAN SOIL AND RICE PADDIES

BROECKER, WALLACE S.

COLUMBIA UNIVERSITY

FY 1991	60
FY 1990	0
FY 1989	0

09/15/91-09/14/92

Objective. To determine how changing land use affects organic carbon storage in soil with the hypothesis that much of the missing carbon in the global carbon budget resides in soils at depths not commonly measured in basic soil surveys; to look at time histories of carbon and nitrogen accumulation under anaerobic conditions of rice paddies, reconstructing burial and decomposition rates of rice chaff from sediment cores of different-aged rice paddies.

Product. Reconstructed carbon and nitrogen inventories of soil profiles in the corn belt and grasslands of central United States that have been subjected to different land uses.

Approach. Organic carbon and nitrogen fractions will be measured for cultivated soils and will be compared with samples collected at undisturbed sites not affected by past agricultural practices. Carbon lost from upper soil layers and deposited in lower soil layers instead of being oxidized to carbon dioxide will be measured. Also, measures of bulk soil density, porosity, moisture content, N/C ratios, ^{14}C, ^{137}Cs, and ^{210}Pb in soil fractions will be used to identify processes of carbon storage in deeper soils as well as to estimate the residence time of various carbon fractions in soils.

SPATIAL AND TEMPORAL PATTERNS OF BIOTIC EXCHANGES OF CO_2 BETWEEN THE ATMOSPHERE AND TROPICAL LANDSCAPES AND THEIR ROLE IN THE GLOBAL CARBON BALANCE

BROWN, SANDRA

UNIVERSITY OF ILLINOIS

FY 1991	102
FY 1990	99
FY 1989	0

09/15/91-09/14/92

Objective. To examine terrestrial sources and sinks for atmospheric CO_2 (1) to determine historical and future spatial-temporal patterns of biotic CO_2 exchange between the tropics and the atmosphere, (2) to determine the long-term (1850-1980) and short-term (1975-1990) annual net tropical carbon flux, (3) to assess the relative importance of mechanisms that control the short-term exchanges, (4) to evaluate the estimated short-term flux with measured variations in atmospheric CO_2, (5) to provide a best estimate of tropical CO_2 flux from 1958 to the present, and (6) to test the hypothesis that CO_2 fertilization has been an important mechanism in the net tropical carbon balance. The present component focuses on Items (3), (5) and (6) with an emphasis on tropical American forests.

Product. A method for converting different types of structural data for forests (inventory of trees by species, diameter, and height from known size plots; 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 American forests; preliminary models for predicting forest biomass for areas where no information is available from the Geographical Information System (GIS); and revised estimates of the biomass of tropical forests for all tropical countries based on the commercial volumes reported in U.N. Food and Agriculture Organization (FAO) publications and new expansion factors.

Approach. 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. All resulting biomass values will be geographically referenced and entered into the GIS.

Results to Date. Digital maps for continental South and Southeast Asia have been produced (Weck's Climatic Index [WCI], precipitation, population density, and biomass densities for inventoried areas) or obtained from various sources (FAO soils, topography, FAO vegetation, and FAO ecofloristic zones) and all loaded and coregistered into ARC/INFO and ERDAS GISs. A potential biomass map for the region was produced with a simple additive model from the maps of the WCI; precipitation; topography; and soil layers of texture, depth and drainage, and slope. The map was calibrated and validated with historical forest data. Potential biomass estimates for the forests ranged from <50 to 650 Mg/ha. The total potential carbon pool for the region was about 100×10^{15} g.

Actual forest biomass for the region as of the early 1980s was produced from the potential map by using the GIS to overlay it on maps of actual vegetation, actual biomass estimates from inventoried areas, and population density along with indices of biomass degradation. Biomass of contemporary forests ranged from <50 to 350 Mg/ha, with a total carbon pool of 16.5×10^{15} g, an 83% reduction from the potential forest carbon pool.

Geographically referenced biomass estimates for the forests of the Brazilian Amazon were made from two large-scale inventories done in the 1950s to 1960s and in the late 1970s. Biomass estimates based on data from the early inventories ranged from 175 to 397 Mg/ha with a weighted mean of 298 Mg/ha. From the later inventory, the range was from 166 to 330 Mg/ha with a weighted mean of 227 Mg/ha. These lower-than-expected biomass estimates are caused by past and present human intervention.

ENERGY AND FUTURE CARBON DIOXIDE EMISSIONS

EDMONDS, JAMES A.

PACIFIC NORTHWEST LABORATORY

FY 1991	389
FY 1990	416
FY 1989	300

10/01/90-09/30/91

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, to support the Department of Energy in its participation in the Intergovernmental Panel on Climate Change, and to support the Department of Energy in its participation in the Committee on Earth and Environmental Sciences.

Product. 1. Representation of the U.S. DOE on the Intergovernmental Panel on Climate

Change, Response Strategies Working Group, Energy and Industry Subgroup (IPCC/RSWG/EIS); representation of the U.S. DOE on the Committee on Earth and Environmental Sciences (CEES); and Version 0.0 of an energy-economic model of CO_2 and other radiative precursor emissions based on the earlier Edmonds/Reilly model.

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

Committee meetings of the CEES will be attended, and quantitative support for DOE participation in the Committee will be provided.

A second generation model will be developed with a general-equilibrium economic structure with sufficient detail to account for all significant greenhouse gases. Version 0.0 will demonstrate not only the concept, but also several computational techniques. Energy activities will be the principal focus of the model, and other economic interactions will be highly aggregated. Version 0.0 will model 11 sectors (agriculture, crude oil, refined oil, natural gas, coal, biomass, uranium, electricity, other products, households, and government) and 12 factors of production (agriculture, crude oil, refined oil, natural gas, coal, biomass, uranium, electricity, other products, land, labor, and capital). Capital stocks will be tracked by year of installation, and international trade will be allowed. A demographic module of population growth will be developed. This model will facilitate the analysis of interactions among population growth, labor force, economic growth, energy use, and greenhouse gas emissions, and this prototype will provide the basis for evolutionary development of the full scale version of this model.

Results to Date. Participated in the United States delegation to the Science Working Group meeting held in Shepperton, United Kingdom. Participating in the global warming potential and the emissions subgroups. Participated in the United States delegation to the International Group of Funding Agencies (IGFA) meeting in Brighton, United Kingdom. Made a presentation on U.S. research in the field of global environmental change for the CEES.

Version 0.0 of the second generation model was completed. Initial model results were presented to the Tokyo Conference on Global Changes and Modelling, Oct. 29-31, 1991.

CARBON CYCLE PROGRAM MANAGEMENT

FARRELL, MICHAEL P.

OAK RIDGE NATIONAL LABORATORY

FY 1991	1265
FY 1990	1262
FY 1989	1529

10/01/90-09/30/91

Task I. Changes in Atmospheric CO_2 and Total-Carbon-Cycle Analysis (A. W. King and W. R. Emanuel)

Objective. To clarify the relationships between fossil-fuel emissions and atmospheric CO_2 concentration that control further CO_2 increases as fossil-fuel use continues and to provide support for DOE in the analysis of the Global Warming Potential (GWP) for CO_2.

Product. Models of the global carbon cycle and underlying data (including descriptions of carbon dynamics in the terrestrial and oceanic reservoirs) and analyses to clarify potential responses of atmospheric CO_2 to further fossil-fuel use; a core terrestrial model of carbon turnover in vegetation, litter, and soil linked to the general features of biosphere-atmosphere CO_2 exchange.

Approach. Observational studies of the phenomena controlling CO_2 concentration are

often impractical because of the time scales involved (decades to centuries), the vast extent and spatial heterogeneity of Earth systems, and the small perturbations to natural levels that fossil-fuel releases cause in very large reservoirs, such as the oceans. Furthermore, many mechanistically important variables cannot be measured directly. Mathematical models are an important means of contending with these limitations of direct studies. They also provide a means of synthesizing the diverse data assembled to address the CO_2 issue and of interpreting those data in terms of changes in atmospheric CO_2 levels.

To estimate changes in atmospheric CO_2 concentration that are caused by different amounts of fossil-fuel use, we must, at a minimum, consider the influences of the oceans, land plants, and dead organic matter and its decomposers in soil. This task takes a total-carbon-cycle approach and integrates data, concepts, and models from the atmospheric, terrestrial, and oceanic projects.

The Carbon Dioxide Information Analysis Center will produce annual updates of emissions estimates. The emissions data set will be based largely on data compiled by the United Nations Statistics Office. These data do not include details of energy end uses that allow analysis of the relationships between CO_2 emissions and socioeconomic factors. With energy data increasingly available in greater accuracy and detail, the accuracy of the data and differences between data sets will be reexamined. The energy end uses most related to CO_2 emissions will also be analyzed to describe where CO_2 emissions are concentrated within the global economy.

Results to Date. We continue to analyze a wide range of carbon-cycle models. The implications of reduced fossil-fuel CO_2 emissions were analyzed in the context of scenarios proposed by the Intergovernmental Panel on Climate Change. Transient responses of CO_2 were compared to those of other greenhouse gases to clarify the applicability of global-warming-potential indices. In a major review of the past decade's progress in carbon-cycle research, we concluded that estimates of past decreases in terrestrial carbon storage because of land use continue to be inconsistent with estimates of oceanic uptake and observed changes in atmospheric CO_2. These inconsistencies restrict confidence in projections of future CO_2 levels and top the agenda for further research.

Task II. Natural and Forced Carbon Turnover in Terrestrial Ecosystems (W. M. Post and V. H. Dale)

Objective. To develop a realistic model of carbon turnover in terrestrial ecosystems as it affects responses to fossil-fuel emissions that treats the dependence of processes on environmental conditions and perturbations by such human activities as land use.

Product. Terrestrial carbon-cycle models and their underlying data sets to be incorporated into the total global-carbon-cycle models described in Task I with land-use summaries provided for specific regions of interest.

Approach. Two classes of models must be merged to realistically describe terrestrial carbon dynamics because, even though the slow circuit of carbon through vegetation and dead organic matter is responsible for significant carbon storage, environmental conditions are also influenced by carbon circuits that respond much more quickly, such as photosynthesis, respiration, translocation, and transpiration in plants and the turnover of microbial decomposers in actively decomposing organic-matter pools.

We cannot simply integrate models that describe the rapid processes of CO_2 diffusion, photosynthesis, fluid transport, respiration, and transpiration in cells and leaves to estimate productivity of whole plants and ecosystems. The nature of the spatial averaging implied in the selection of parameters and processes to be included is difficult because of nonlinearities.

For example, photosynthesis models assume uniform biochemical concentrations over an entire plant, a condition rarely found outside the laboratory. Furthermore, computational error accumulates when small deviations are multiplied by scaling factors or continue for long t me periods.

Important carbon-storage responses to changing environmental conditions will be clarified by exercising a number of models, initially without concern as to how they might be organized for global-scale applications. Based on the experience, two modules that address carbon dynamics with two sets of characteristic response times will be formulated. A rapid-dynamics module will describe CO_2 exchanges, photosynthesis, water loss, and energy balance for a prototype leaf or photosynthetic unit. And a slow-dynamics module will represent ecosystem carbon storage as a compartmental system of living and dead components and the fluxes between them.

Results to Date. It appears likely that variations in environmental conditions, including the steady increase in atmospheric CO_2 concentration, have influenced terrestrial carbon cycling in many regions. These variations have partially compensated for land-use impacts by maintaining carbon sinks, such as those identified by Tans and co-workers through an analysis of atmospheric and surface water CO_2 data. We developed a model of terrestrial carbon cycling that treats the influence of environmental conditions to assess these possibilities.

The model represents carbon cycling on the ten continental regions used by Houghton and co-workers to analyze land-use data. Carbon in each ecosystem is divided into vegetation, litter, and soil compartments. An area distribution function further describes variations in the density of carbon in vegetation. Land use, such as forest harvest or forest clearing, alters this area distribution function.

The model relates the uptake of carbon from the atmosphere by net primary production (NPP) to temperature by a growing-degree-day index and to moisture by a drought index and tolerance factor. An empirical function derived from controlled-CO_2 plant-growth experiments describes the dependence of NPP on atmospheric CO_2 concentration. The release of CO_2 from dead organic matter by decomposition depends on temperature according to a Q_{10} function.

Land use forces changes in the area distribution functions for vegetation carbon densities in the ecosystems involved. Forest harvest and forest clearing have been included thus far. At first, land-use data summarized by Houghton and co-workers is being used as a basis for comparison with previous results. But efforts are under way to summarize more-detailed land-use data from critical regions, including Brazil and South and Southeast Asia. These data will be analyzed in this new model as well.

The new terrestrial model is designed for standalone use or it can be coupled to a variety of models of carbon turnover in the atmosphere and oceans. Initially, 1-D ocean models calibrated to the distributions of natural or weapons-produced radiocarbon are being used. But comparisons with other ocean models, including our own lateral-transport model and published results from oceanic general circulation models, are being continued.

Task III. Extending Testing of the Importance of Oceanic Processes in Controlling Atmospheric CO_2 (T.-H. Peng)

Objective. To improve the representation of oceanic carbon cycling in models and to interpret new oceanic data in terms of changing atmospheric CO_2 concentration.

Product. Refinements to oceanic carbon-cycle models and analyses of ocean data in terms of the influence of the oceans on atmospheric CO_2 responses to fossil-fuel emissions.

Approach. Mathematical models of carbon turnover in the oceans are continually refined to

incorporate more-realistic descriptions, to take advantage of new data, and to use insights gained in the development of oceanic-circulation models. We will use these models to clarify the control of the oceans over atmospheric CO_2 concentration. In addition to the fossil-fuel era, we will investigate climate-induced changes in oceanic carbon turnover indicated by our paleooceans model, emphasizing the formation and demise of North Atlantic deep water, a major force in ocean circulation.

The Global Ocean Flux Study (GOFS) will yield new data on the role of marine organisms in oceanic element cycling. We will evaluate the implications of GOFS data as they become available. The immediate objectives will be to determine the biological processes that must, at a minimum, be explicitly considered in the analysis of changes in atmospheric CO_2 levels and to incorporate a representation of these processes into our reference models. This activity will provide an avenue for bringing results from DOE's oceans program into the development of total-carbon-cycle models.

Results to Date. We have developed a model that includes lateral transport within the major oceans. The model is based on the distribution of weapons-testing ^{14}C measured by the GEOSECS program. Independent flow and mixing patterns describe carbon dynamics in the Atlantic, Pacific, and Indian oceans. But the appropriate linkage of these components is critical, especially with respect to the role of Antarctic circumpolar waters. Although the Antarctic waters are the most important linkage, other connections are important, including the Indonesian archipelago and Agulhas current flows at the southern tip of Africa. Carbon-cycle models are also being used to analyze schemes for mitigating CO_2 increases. Ocean model studies indicate that one proposal, adding iron to regions of high biological productivity in the southern oceans, is largely impractical because the iron additions must be continued indefinitely while fossil-fuel emissions continue and must be applied so as to stimulate productivity where it contributes to substantial detrital rain to sediments.

SIMULATIONS OF THE CARBON CYCLE IN THE OCEANS

FASHAM, MICHAEL J. R.

INSTITUTE OF OCEANOGRAPHIC SCIENCES

FY 1991	102
FY 1990	102
FY 1989	0

08/15/91-08/14/92

Objective. Developing a 3-D model of the ocean carbon cycle requires three related components of research. The goal is to develop a prognostic model of the ocean carbon cycle that can be used to predict future increase of atmospheric CO_2 from human activities. Objectives of the Institute of Oceanographic Sciences (Fasham) component are (1) to develop 3-D models of the ocean carbon cycle and to test a carbon/nitrogen mixed-layer ecosystem model against data sets for the North Atlantic; (2) to analyze carbon/nitrogen ecosystem components for a 3-D North Atlantic simulation; and (3) to embed equations of the North Atlantic ecosystem model into the 3-D ocean GCM and to extend the ecosystem model to deeper ocean layers.

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

Approach. This research aims to predict the role of biological populations in the uptake and recycling of CO_2 in the upper ocean with simple coupled carbon and nitrogen ecosystem models. Models of gradually increasing complexity will be tested with integrated mixed-layer or 1-D models of the physical processes, and the results will be compared with suitable data sets. The resulting models and their associated parameter sets will

then be embedded in various 3-D physical models developed at Princeton University for the prediction of basin-scale and global effects. The ultimate aim is to develop a model that is geographically robust in the sense that a single model and parameter set coupled with geographically varying physical forcing will reproduce the observed variability in biological production and CO_2 uptake.

Results to Date. A carbon-based biological model of the upper ocean has been completed and incorporated into the Atlantic General Circulation Model developed by J. L. Sarmiento et al. at Princeton University. The model considers in detail the coupling of carbon and nitrogen in the marine environment and how this coupling influences trophic interactions. Carbonate chemistry and air-sea carbon fluxes are also considered in detail. Model results demonstrate the importance of marine phytoplankton in depressing the partial pressure of CO_2 in surface waters, the significance of zooplankton grazing in controlling phytoplankton biomass, and hence system dynamics in general.

Particular attention has been paid to the relationship between amounts of nitrogen excreted (important for phytoplankton growth) and carbon respired (important in the marine carbon cycle) by zooplankton and bacteria. This relationship is by no means simple. It depends on grazing and respiration rates and on the carbon and nitrogen contents of both predator and prey items. Results suggest that zooplankton growth may be limited by the availability of carbon in their prey. The model highlights the fact that the way in which respiration is treated is of major significance in determining remineralization rates of carbon and nitrogen by zooplankton and bacteria.

SPATIAL AND TEMPORAL PATTERNS OF BIOTIC EXCHANGES OF CO_2 BETWEEN THE ATMOSPHERE AND TROPICAL LANDSCAPES AND THEIR ROLE IN THE GLOBAL CARBON BALANCE

FUNG, I. Y.-S

GODDARD INSTITUTE FOR SPACE STUDIES

FY 1991	104
FY 1990	101
FY 1989	0

09/15/91-09/14/92

Objective. To examine terrestrial sources and sinks for atmospheric CO_2 (1) to determine historical and future spatial-temporal patterns of biotic CO_2 exchange between the tropics and the atmosphere, (2) to determine the long-term (1850-1980) and short-term (1975-1990) annual net tropical carbon flux, (3) to assess the relative importance of mechanisms that control the short-term exchanges, (4) to evaluate the estimated short-term flux with measured variations in atmospheric CO_2, (5) to provide a best estimate of tropical CO_2 flux from 1958 to the present, and (6) to test the hypothesis that CO_2 fertilization has been an important mechanism in the net tropical carbon balance. The present component focuses on Item (6) with the specific objective of analyzing global patterns of atmospheric CO_2 circulation based on carbon exchange between terrestrial ecosystems and the atmosphere from deforestation and other changes in land use.

Product. Analysis of net flux of carbon to the atmosphere as a result of land-use changes, especially in the tropics, based on satellite data and estimates of atmosphere-biosphere CO_2 exchange consistent with observed concentrations and gradients of atmospheric CO_2.

Approach. This component will use data on land use, biomass, and soil-carbon changes in an atmospheric CO_2 exchange model in the analysis of regional sources and sinks for CO_2. Calculated net flux based on changes in surface properties will be compared with observed geographic variations in atmospheric concentrations of CO_2. An atmospheric CO_2 circulation model will be used to investigate the distributions of atmospheric CO_2 from different scenarios of land-use modification. The evaluation will be based on three analyses: checking the data for internal consistency and attempting to calculate the annual net flux of carbon with them; comparing the carbon flux calculated with this data with the flux calculated previously by different methods; and defining the sample size appropriate for detailed analyses with a Monte Carlo approach.

Results to Date. CO_2 release from land-use modification and fossil-fuel burning were combined with CO_2 exchanges with the biosphere and the ocean in a 1-D model as well as in a global 3-D general-circulation model (GCM) to test the consistency of CO_2 budget source/sink hypotheses. The models include the exchanges of $^{13}CO_2$ in addition to total CO_2.

The 1-D model is a box-diffusion model based on the formulation of Oeschger and Siegenthaler (1976), where the oceanic mixing parameters are calibrated by natural and bomb ^{14}C. The model is used to simulate the time history of CO_2 and $^{13}CO_2$ balance since the preindustrial era. New observations of the change in the ^{13}C signal in the oceanic mixed layer provide new constraints on the oceanic uptake of anthropogenic CO_2. Sensitivity experiments with the 1-D model demontrate very clearly that a sole ocean sink, obtained with unrealistic oceanic mixing parameters, causes a lowering of the mixed-layer ^{13}C by an amount larger than that observed; viz. a terrestrial sink is required. This result is in agreement with published studies on the balance of total CO_2 using the 1-D model. While the net terrestrial flux required to match the time series of CO_2 in the atmosphere can be obtained as a residual in the carbon balance, matching the ^{13}C time series is nontrivial. In particular, the result is very much dependent on the active size of the biosphere and the residence time of carbon there.

The 3-D global model was used to simulate the distribution of $^{13}CO_2$ in the atmosphere for different assumptions of source/sink balance in the 1980s. As in the 1-D model, the north-south gradient of atmospheric $^{13}CO_2$ was found to be very sensitive to the values assumed for biospheric reservoir size and carbon residence time. While the results at this stage cannot be used to constrain the contemporary carbon budget, the sensitivity studies identify the research necessary to achieve that goal. Ongoing research will focus on developing a terrestrial carbon model that is constrained by the ^{13}C data. It is hoped that the results will provide insight into the mechanism in addition to the location of the terrestrial carbon sink.

SPATIAL AND TEMPORAL PATTERNS OF BIOTIC EXCHANGES OF CO_2 BETWEEN THE ATMOSPHERE AND TROPICAL LANDSCAPES AND THEIR ROLE IN THE GLOBAL CARBON BALANCE

HALL, CHARLES A. S.

STATE UNIVERSITY OF NEW YORK

FY 1991	146
FY 1990	75
FY 1989	0

09/15/91-09/14/92

Objective. To examine terrestrial sources and sinks for atmospheric CO_2 (1) to determine historical and future spatial-temporal patterns of biotic CO_2 exchange between the tropics and the atmosphere, (2) to determine the long-term (1850-1980) and short-term (1975-1990) annual net tropical carbon flux, (3) to assess the relative importance of mechanisms that control the

short-term exchanges, (4) to evaluate the estimated short-term flux with measured variations in atmospheric CO_2, (5) to provide a best estimate of tropical CO_2 flux from 1958 to the present, and (6) to test the hypothesis that CO_2 fertilization has been an important mechanism in the net tropical carbon balance. The present component focuses on Items (3), (4), and (6) with the broad objective of providing more-precise estimates of the net flux of CO_2 to the atmosphere from land-use changes in the tropics.

Product. Updated assessments of the exchange of carbon between tropical landscapes and the atmosphere, including sensitivity analyses.

Approach. Biomass of tropical forests and changes in the standing stock of carbon from indigenous degradation (i.e., the effects of shifting agriculture on the carbon content of ecosystems) related to land-use change and other social influences will be analyzed. The effort will concentrate on Central America and will involve sensitivity analysis of different landscape properties and clearing practices on the release of CO_2. The analysis will consider carbon assimilation by tropical forests during regrowth, thus emphasizing the sink term of global carbon balance. Data will be used by Houghton to calculate net CO_2 exchange involving global tropical forests.

Results to Date. This year we continued to focus upon the relationship between refining estimates of land-use change and refining our model of carbon exchange within terrestrial ecosystems. Much of the uncertainty of the magnitude of carbon exchange with and within terrestrial systems is a result of the way in which current models partition carbon into aggregated land-use types. Spatially explicit models can reduce this uncertainty by distributing carbon into more-precise land-use types or by incorporating various estimates of certain types of land use, such as shifting cultivation, which may be proportionally significant but are often overlooked. Indeed, we have found that when shifting cultivation in particular is not taken into account, our current models underestimated the release of carbon from the entire tropics by 20%. By comparing estimates of land-use change from international sources, such as the FAO and more locally specific and detailed sources, this uncertainty may be further reduced. We are beginning to integrate our carbon-exchange models with GIS models of past and future land-use change to further refine our analyses.

SPATIAL AND TEMPORAL PATTERNS OF BIOTIC EXCHANGES OF CO_2 BETWEEN THE ATMOSPHERE AND TROPICAL LANDSCAPES AND THEIR ROLE IN THE GLOBAL CARBON BALANCE

HOUGHTON, R. A.

WOODS HOLE RESEARCH CENTER

FY 1991	212
FY 1990	222
FY 1989	0

09/15/91-09/14/92

Objective. To examine terrestrial sources and sinks for atmospheric CO_2 (1) to determine historical and future spatial-temporal patterns of biotic CO_2 exchange between the tropics and the atmosphere, (2) to determine the long-term (1850–1980) and short-term (1975–1990) annual net tropical carbon flux, (3) to assess the relative importance of mechanisms that control the short-term exchanges, (4) to evaluate the estimated short-term flux with measured variations in atmospheric CO_2, (5) to provide a best estimate of tropical CO_2 flux from 1958 to the present, and (6) to test the hypothesis that CO_2 fertilization has been an important mechanism in the net tropical carbon balance. The present component focuses on Item (5).

Product. A refined range of estimates of the net flux of carbon to the atmosphere from tropical deforestation and reforestation for the 1980s and

new estimates of the integrated flux between 1850 and 1990.

Approach. Existing statistics on carbon content of vegetation and soils will be assembled, and a simple carbon balance model will be used to estimate CO_2 flux. The analysis will concentrate on changes involving tropical forests; however, the estimates will be combined with data from other geographic areas to provide a global estimate of the CO_2 flux from land clearing and other human influences. As new data are reported in the open literature, they will be promptly incorporated into the global CO_2 analysis.

Results to Date. No results reported.

A STUDY OF THE ABUNDANCE AND $^{13}C/^{12}C$ RATIO OF ATMOSPHERIC CARBON DIOXIDE AND OCEANIC CARBON IN RELATION TO THE GLOBAL CARBON CYCLE

KEELING, CHARLES D.

SCRIPPS INSTITUTION OF OCEANOGRAPHY

FY 1991	268
FY 1990	250
FY 1989	0

03/01/91-02/14/92

Objective. To continue high-precision and high-accuracy measurements of atmospheric CO_2 at the Mauna Loa Observatory and to expand measurements of $^{13}C/^{12}C$ isotopic ratios of CO_2 for distinguishing the biological and oceanic carbon processes undergoing change.

Product. A data base for calibrating atmospheric CO_2 circulation models and for evaluating sources and sinks of exchange with oceans and the terrestrial biosphere.

Approach. High-precision CO_2 and isotopic measurements will be carried out at background air pollution monitoring stations of the Central Pacific region (e.g., the Mauna Loa, Hawaii location). Atmospheric CO_2 data will be collected at additional sites to create a data base for validating 3-D models of atmospheric and oceanic transport of carbon in the atmosphere and oceans. These models will be used to predict atmospheric CO_2 in relation to changing processes and properties of the global carbon cycle.

Results to Date. Sea-water samples have been collected in duplicate on Legs 1 (347 samples) and 2 (220 samples) of the WOCE Hydrographic Survey in the Pacific Ocean. Samples have been received and are being analyzed at our laboratory. Samples are currently being collected on Leg 3 to complete the field program for 1991. Measurements include dissolved inorganic carbon by manometric analysis, alkalinity by potentiometric titration, and salinity and nutrients by conventional methods. Laboratory measurements will be used to validate measurements made on board ship.

TENTH INTERNATIONAL SYMPOSIUM ON ENVIRONMENTAL BIOGEOCHEMISTRY

OREMLAND, RONALD S.

INTERNATIONAL SYMPOSIA ON ENVIRONMENTAL BIOCHEMISTRY, INC.

FY 1991	15
FY 1990	0
FY 1989	0

12/15/90-12/14/91

Objective. To conduct the Tenth International Symposium on Environmental Biogeochemistry.

Product. Dissemination of scientific findings in biogeochemistry to the international scientific community, thereby fostering interdisciplinary communication and research among scientists around the globe.

Approach. ISEB-10 will consist of invited and contributed papers to be presented in oral plenary sessions and poster sessions. The theme of ISEB-10 will be "Global Change and the Biogeochemistry of Radiative Trace Gases". Program topics will include paleoatmospheres, paleoclimates, and past climate changes; global atmospheric distributions and reactions of radiative trace gases; microbial mechanisms of formation and consumption of radiative trace gases; exchange of trace gases in agricultural ecosystems; radiative trace gases from biomass burning; gas-exchange studies in high-latitude environments; and global budgets, ecosystem cycling, geological and industrial sources, and feedback effects of radiative trace gases.

NATO ADVANCED STUDY INSTITUTE ON THE GLOBAL CARBON CYCLE

PEARMAN, GRAEME

COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANISATION

FY 1991	15
FY 1990	0
FY 1989	0

08/15/91-08/14/92

Objective. To expose young scientists from countries around the world to the best information about the carbon cycle from atmospheric scientists, terrestrial ecosystem scientists, and oceanographic scientists and to bring together senior scientists in these fields in a workshop framework.

Product. Advanced understanding of the global carbon cycle.

Approach. A major NATO Advanced Studies Institute that will focus on the global carbon cycle and that will be held in Italy on September 8-22, 1991, will be coordinated and organized.

SPATIAL AND TEMPORAL PATTERNS OF BIOTIC EXCHANGES OF CO_2 BETWEEN THE ATMOSPHERE AND TROPICAL LANDSCAPES AND THEIR ROLE IN THE GLOBAL CARBON BALANCE

RICHARDS, JOHN F.

DUKE UNIVERSITY

FY 1991	100
FY 1990	98
FY 1989	0

09/15/91-09/14/92

Objective. To examine terrestrial sources and sinks for atmospheric CO_2 (1) to determine historical and future spatial-temporal patterns of biotic CO_2 exchange between the tropics and the atmosphere, (2) to determine the long-term (1850-1980) and short-term (1975-1990) annual net tropical carbon flux, (3) to assess the relative importance of mechanisms that control the short-term exchanges, (4) to evaluate the estimated short-term flux with measured variations in atmospheric CO_2, (5) to provide a best estimate of tropical CO_2 flux from 1958 to the present, and (6) to test the hypothesis that CO_2 fertilization has been an important mechanism in the net tropical carbon balance. The present component focuses on Items (1) and (2).

Product. Time-series data on carbon balance for land components (vegetation and soil) in relation to agriculture and increased population in Southeast Asia and Central/South America.

Approach. A historical record of land use, which is important for the first approximation of pre-industrial CO_2 flux from human influences, will be produced. These reference data, when combined with fossil fuel CO_2 emissions, will be valuable for modeling the time history of the global carbon cycle. No alternative approaches exist for reconstructing this type of information.

Area figures for land use at each level will be converted 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.

Results to Date. Corrections and revisions of time series data for South and Southeast Asia have been completed. Estimates of land-use change and changes in carbon stocks have been published in "Historical Analysis of Changes in Land Use and Carbon Stock of Vegetation in South and Southeast Asia," *Can. J. Forest Res.* 21, 91-110 (1991). Extensive bibliographical effort has been devoted to identify and obtain a wide range of data for land-use changes in Central and South America. Tabular estimates for land use/land cover have been completed for seven countries for 1850 to 1990. Research on the remaining countries is now under way.

SIMULATIONS OF THE CARBON CYCLE IN THE OCEANS

SARMIENTO, JORGE L.

PRINCETON UNIVERSITY

FY 1991	286
FY 1990	263
FY 1989	0

08/15/91-08/14/92

Objective. To develop a prognostic model of the ocean carbon cycle that can be used to predict future increase of atmospheric CO_2 from human activities. Objectives of the Princeton component are to develop 3-D models of the ocean carbon cycle and perform the fixed-atmosphere CO_2 simulation with nonseasonal and seasonal ocean circulation; to predict background total carbon fields and to use a seasonal 3-D North Atlantic ecosystem model to do carbon and nitrogen simulations; and to perform simulations with a global carbon cycle ecosystem model to estimate anthropogenic CO_2 uptake by oceans.

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. Two parallel approaches will be used. The first will assume that the pre-anthropogenic ocean carbon cycle continues to operate without being affected directly by anthropogenic perturbations. This "steady state" approach will enable us to treat the anthropogenic CO_2 as a passive tracer. The only information we will need regarding the carbon cycle, other than the appropriate thermodynamic constants, is the pre-anthropogenic surface total carbon and alkalinity concentrations. The second approach will assume that the oceanic carbon cycle will quite likely respond dynamically to the effect of the anthropogenic greenhouse gas perturbations on climate. Ecosystem models of this situation will be incorporated into our ocean-circulation models.

Results to Date. Estimates from world ocean general-circulation simulations of CO_2 uptake, recent models of atmospheric transport, and measurements of air-sea CO_2 exchange have led us to propose a new view of the ocean carbon cycle. The preindustrial ocean carbon balance requires an outward air-sea flux of 0.6 GtC/y to balance net inflow from rivers minus loss from sediments. Therefore, the present total uptake of 2 GtC/y must be split between an air-sea input of 1.4 GtC/y and a net preindustrial river-minus-sediment input of 0.6 GtC/y.

The potential for mitigating ever-increasing atmospheric CO_2 via iron fertilization has been studied with our world ocean general circulation model. Results show that after 100 years, if fertilization were completely effective in removing all nutrients from the surface ocean south of 31°S, a maximum of 61 to 72 ppm of additional CO_2 could be absorbed by the oceans. Fertilization in other regions is not as effective; only an additional 2 ppm would be absorbed when fertilization was confined to equatorial waters, 7 ppm when confined to the North

Atlantic, and 13 ppm when confined to the North Pacific. Some regional anoxia and low oxygen conditions would develop and would clearly impact local ecology.

Recently, N_2O has been added to the iron-fertilization model to simulate additional production of N_2O during remineralization of organic material. After 100 years, 58% of the additional N_2O can be found in the atmosphere, giving a perturbation pN_2O of 42 ppb. This increase in N_2O would reduce the beneficial greenhouse effect of any CO_2 removal via iron fertilization.

Paleooceanographic implications of high-latitude nutrient depletion are under investigation with the nutrient-depletion model. Equilibrium simulations (1600 years) have exhibited distributions of phosphate that resemble real-world data for cadmium(II), a proxy for phosphate in the paleo-ocean. Preliminary results of a simulation without sedimentary dissolution of $CaCO_3$ show atmospheric CO_2 dropping from its preindustrial value of 280 ppm to 208 ppm. Dissolution of $CaCO_3$ would increase this reduction.

A carbon/nitrogen ecosystem model has been incorporated into the Atlantic circulation model. This new ecosystem model incorporates several changes to the modeling of zooplankton, changes that have greatly improved the simulation of the seasonal evolution of phytoplankton in the surface ocean, bringing them into better agreement with satellite observations.

SIMULATIONS OF THE CARBON CYCLE IN THE OCEANS

SIEGENTHALER, U.

UNIVERSITY OF BERN

FY 1991	50
FY 1990	52
FY 1989	0

08/15/91-08/14/92

Objective. To help in the continued development of 3-D models of the oceanic carbon cycle for simulating the ocean's uptake of anthropogenic CO_2.

Product. Three-dimensional simulations of anthropogenic CO_2 uptake with indications of the sensitivity of that uptake to various factors; simulations with a 1.5-D model; comparisons of the 3-D model results with those of the 1.5-D model to better understand the use of simple models as economical substitutes for 3-D models.

Approach. The 3-D model runs will be carried out at Princeton University. The University of Bern will help to plan and evaluate the model experiments, based on our experience with simple carbon-cycle models. Simple models that allow extensive sensitivity tests and comparison of different oceanic tracer fields will be developed and used. Circulation and tracer fields from the 3-D model will be projected to one and two dimensions for deriving parameterized transport coefficients comparable to those used in simple models.

Results to Date. A 1.5-D diffusion-advection ocean model (HILDA) including a high-latitude box has been used for studying cycling and distribution of various properties. We found that to reproduce the oceanic distributions of natural and bomb-produced ^{14}C, a depth-dependent vertical eddy diffusivity, decreasing with depth, has to be assumed. Apparent eddy diffusivities derived from the Princeton 3-D ocean model are, indeed, highest in the top few 100 m, indicating that circulation is most vigorous near the surface. The HILDA model has been applied to study the potential reduction of the atmospheric CO_2 growth by a hypothetical fertilization of the Southern Ocean with iron. It was assumed that iron fertilization is fully effective from 1990 on in the whole Southern Ocean. For a business-as-usual scenario, atmospheric CO_2 would increase from 1990 to 2090 by 417 ppm without iron fertilization and by 310 ppm with it. Iron fertilization thus could not reverse the increasing CO_2 trend; the most

effective strategy for reducing future CO_2 increases continues to be the control of man-made emissions.

SPATIAL AND TEMPORAL PATTERNS OF BIOTIC EXCHANGES OF CO_2 BETWEEN THE ATMOSPHERE AND TROPICAL LANDSCAPES AND THEIR ROLE IN THE GLOBAL CARBON BALANCE

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

UNIVERSITY OF NEW HAMPSHIRE

FY 1991	100
FY 1990	144
FY 1989	0

09/15/91-09/14/92

Objective. To examine terrestrial sources and sinks for atmospheric CO_2 (1) to determine historical and future spatial-temporal patterns of biotic CO_2 exchange between the tropics and the atmosphere, (2) to determine the long-term (1850–1980) and short-term (1975–1990) annual net tropical carbon flux, (3) to assess the relative importance of mechanisms that control the short-term exchanges, (4) to evaluate the estimated short-term flux with measured variations in atmospheric CO_2, (5) to provide a best estimate of tropical CO_2 flux from 1958 to the present, and (6) to test the hypothesis that CO_2 fertilization has been an important mechanism in the net tropical carbon balance. The present component focuses on Items (1) and (4).

Product. Maps and spatial integration of data on forest composition and on areas of land-use change based on satellite observations (e.g., Landsat and AVHRR).

Approach. The vast amount of observation from space will be used to detect changes in the distribution of vegetation as a cost-effective way of quantifying areal changes of land use, an important term in the equation for first-approximation estimates of carbon stocks for tropical forests.

Results to Date. This analysis suggests that 0.4 to 0.6 x 10^{15} g of carbon were released annually since 1958. Most of the net flux was derived from biomass burning in closed forests during the latter part of the time period. The results are uncertain because of the lack of detailed estimates of biomass, soil organic matter, and deforestation rates. These results can be improved with remote-sensing data.

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 will respond (e.g., atmospheric energy balance is modified with temperature expected to increase; and ocean physical and chemical characteristics are expected to change). The many complex interactions within the climate 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, data collection, and 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 responds to increased concentrations of greenhouse gases. The primary information needs are:

- the rate of the regional climate change and
- 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, why the models respond as they do must be understood. And to provide the regional rate and magnitude of climate change, the models must be developed further.

Research Objectives. This component of the research effort seeks to develop and improve our capabilities to estimate the range of global and regional climate change resulting from increasing CO_2. Research interests include, but are not limited to, the rate and magnitude of changes in such climate parameters as temperature, precipitation, and frequency of extreme events, including changes in the variability of these quantities.

A second objective is to detect evidence of the climate 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 and continued 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 useful in the analyses involving 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 climate change?

- Can a climate response to the greenhouse gases, particularly CO_2, be observed? If not, can it be estimated as to when the signal might be expected to rise above the natural climate variability?

- What are the information requirements for resource analysis?

Computer Hardware, Advanced Mathematics, and Model Physics (CHAMMP)

Evaluating the importance of the future response of regional climates to the increasing atmospheric concentration of greenhouse gases will require advanced climate models capable of much longer and more numerous simulations, finer resolution, and significant improvements in their representation of the physics and chemistry of the climate system. Developing an advanced climate model (ACM) with such capabilities will require computers capable of increasing throughput by a factor of at least 10^4, mathematical formulations and software that use the extensive parallelism of the emerging generations of computers, and improved algorithms that have been more thoroughly verified with more-comprehensive sets of field observations that are currently available.

The CHAMMP initiative will develop an ACM employing the hardware and software capabilities offered by emerging computer architectures to address the challenging physics of the climate system. The objectives of CHAMMP are phased over ten years. In the near term (2 to 3 years), improved performance of existing climate-system models will be achieved by taking advantage of emerging parallel-computing architectures. In the intermediate term (3 to 6 years), an initial scalable version of the climate-system model components of the potential ACM will be designed and developed that is capable of achieving in excess of 100-gigaflop performance. And in the extended term (6 to 10 years), the initial versions of the ACM components will be improved and assessed, an optimized ACM will be assembled, and detailed research calculations will be initiated that will be faster by a factor of 10^4 or more than present speeds achieved on the CRAY-2.

The CHAMMP initiative is designed to bring study of the climate system to the forefront of scientific problems, taking advantage of the developing computational capabilities under way as part of the DARPA TeraOp initiative and the Federal High Performance Computing and Communications Program. Collaboration and coordination with these initiatives will be an integral part of the CHAMMP initiative.

Program Managers
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Research Summaries

SUPPORT FOR ACTIVITIES OF THE POLAR RESEARCH BOARD, NAS

ABBOTT, SHERBORNE

NATIONAL ACADEMY OF SCIENCES

FY 1991	35
FY 1990	35
FY 1989	0

03/01/91-02/28/92

Objective. To advise on U.S. and international policies and 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. (1) Advice to federal agencies on their polar programs when requested as well as on U.S. interests in the polar regions. (2) Representation of the U.S. on the Scientific Committee on Antarctic Research (SCAR) of the International Council of Scientific Unions and on the International Arctic Science Committee (IASC). (3) Ongoing studies that assess the status of research needs in the various disciplines of polar science and recommend promising directions for future research; research priorities; and the facilities, data management, and logistics support required to achieve the recommended research goals. (4) A semiannual forum for the exchange of information about federal activities in polar regions and about research plans. (5) Encouragement of U.S. awareness of and cooperation in international research and data-sharing on the polar regions. (6) An awareness of other activities of the National Research Council that relate to the polar regions.

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 periodically brief the Board. Advice, guidelines, and recommendations on polar research that result from interactions 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 will be profferred.

Results to Date. No results reported.

COMMITTEE ON EARTH AND ENVIRONMENTAL SCIENCES' WORKING GROUP ON GLOBAL CHANGE (WGGC)

ANDERSON, PATRICIA A.

COMMITTEE ON EARTH AND ENVIRONMENTAL SCIENCES

FY 1991	183
FY 1990	0
FY 1989	0

07/01/91-06/30/92

Objective. To provide partial support for six activities supported by the Committee on Earth and Environmental Sciences (CEES) Working Group on Global Change (WGGC) and a provision for contingency.

Product. The efficient collection and distribution by a central body of legitimate and necessary costs for activities that are shared by agencies participating in the Global Change Research Program.

Approach. The National Science Foundation has the task of collecting funds for the CEES and distributing these funds for activities supported by the CEES as agreed to by all participating agencies. For FY 1991, the following activities will be supported:

- The National Academy of Sciences's Committee on Global Change Research (CCGR) for activities related to global change
- The University Corporation for Atmospheric Research (UCAR) to support the UCAR-sponsored FY 1991 Summer Institutes Program on Global Land-Use/Cover Change
- Printing costs for CEES WGGC documents, such as the FY 1991 *U.S. Global Change Research Program*
- The development of software for use in planning, management, and analysis of the USGCRP
- The Intergovernmental Panel on Climate Change (IPCC) to support science-related activities involving workshops and meetings of the Response Strategy Working Group
- An initial workshop on the concept of a Western Hemisphere Regional Center for Global Change Research
- A contingency fund for unforeseen expenses

In addition, the printing costs for global change research documents prepared by the Committee on Earth Sciences of the Office of Science and Technology Policy and printed by Joint Oceanographic Institution, Inc., through a contract with the NSF will be supported.

CLIMATE SYSTEM RESEARCH - STUDIES OF GLOBAL AND REGIONAL INSTRUMENT DATA

BRADLEY, RAYMOND S.

UNIVERSITY OF MASSACHUSETTS

FY 1991	185
FY 1990	199
FY 1989	170

12/01/90-11/30/91

Objective. To extend the DOE long-term surface climate data set for regional analysis; to analyze the data for critical regions with special climate characteristics likely to change under CO_2-induced climate change; to assess the spacial and temporal coherence of hydrologic variability; and 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 and similarly improved and updated precipitation coverage.

Approach. The basic climate data set (prepared at the University of East Anglia) will be improved by assessing the quality of additional temperature and precipitation measurements from the USSR. These data, obtained under a USA/USSR bilateral agreement, will be examined and incorporated into the data set. Because the USSR is large and the data may significantly influence Northern Hemispheric averages (e.g., surface air temperatures), the significance of the additional data will be evaluated.

Because models and paleoclimate analyses suggest that high-latitude and high-altitude environments and arid and semiarid marginal zones will be sensitive to climate change, special regional data bases will be developed for these areas. These data will include sea ice, surface

and low-level atmospheric temperatures, and precipitation. Evidence for climate change in these regions relative to global changes will be evaluated.

The data sets will be analyzed for patterns of regional and hemispheric climatic change and will be compared with GCM projections of greenhouse gas-induced climatic change.

Results to Date. A comprehensive precipitation data set for global land areas, containing more than 5300 station records, has been produced. Analysis of this data set confirmed our earlier report of a precipitation increase over land areas from the 1920s to the early 1970s; precipitation appears to have declined in recent years, but a substantial drop in station data during this period makes this a tentative conclusion. Temperature data were updated through 1990, but changes in coverage and gridding procedures have caused some problems, requiring a reassessment of these data, which is currently under way. High-altitude-station data from remote and pristine environments reveal temperature changes similar to (but smaller than) those observed in adjacent, more urban, environments. Climatic changes in sensitive environments have been studied to determine their relationship to larger-scale (i.e., hemispheric and global) changes. The effects of ENSO events and of explosive volcanic eruptions on global and regional climates has also been examined. Low-level inversions are a semipermanent feature of the polar regions, where the greatest temperature changes are expected as greenhouse gases increase in the atmosphere. Analysis shows a strong relationship between inversion depth and temperature; it also shows systematic changes in Arctic inversion depth during recent decades. Further analysis of Antarctic data is in progress.

GEOCHEMICAL CONSTRAINTS ON OCEAN GENERAL-CIRCULATION MODELS: GLACIAL TERMINATIONS AND THE GLOBAL WATER BUDGET

BROECKER, WALLACE S.

LAMONT-DOHERTY GEOLOGICAL OBSERVATORY

FY 1991	184
FY 1990	0
FY 1989	0

12/01/90-11/30/91

Objective. To transform the data on tracers (such as salt) in the oceans into a form that will allow us to determine the timing and abruptness of the glacial termination, to unravel the mixtures in the ocean, and to facilitate the process of evaluating ocean general-circulation models (GCMs) and assess the extent to which these simulations replicate the present day ocean.

Product. An ability to test ocean GCMs against historic data and, through that, a better understanding of the potential for changes in Atlantic Ocean circulation.

Approach. As water from rivers enters and becomes part of the ocean, the processes of mixing can be tracked and unraveled by looking at tracers, like salt and heat, that are conserved (i.e., they are not significantly altered by processes taking place within the body of the sea). Observing such tracers in the ocean allows us to separate the contributions of different source waters to a given deep-water sample. However, tracer fields are influenced by two quite different processes: mixing among waters descending from different regions and remineralization of the constituents of biological material. For the tracer data to be useful, the influence of these two processes on the distribution of a given tracer must be separated. Unfortunately, salinity and potential temperature

alone do not permit the mixtures that exist in the ocean's interior to be unraveled because the composition of North Atlantic deep water (NADW) covers such a large range of potential temperature (1 to 4°C).

PO_4* has been proposed as a potentially conservative property. PO_4* creatively combines PO_4 and O_2 measurements and allows the mixtures in the Atlantic to be unraveled. Once this separation has been accomplished, the amount of O_2 lost to respiration, the amount of alkalinity gained through $CaCO_3$ dissolution, the amount of SiO_2 gained through opal dissolution, and the amount of radiocarbon and radioargon lost by radioactive decay can be computed for any given water sample from the deep Atlantic. The former data provide powerful constraints on the biological parameterization adopted in ocean GCMs. The latter data provide powerful constraints on rates of ventilation of the deep ocean created by the model's dynamics.

To improve understanding of the large and sudden changes of climate associated with glacial time, the interaction between water vapor transport through the atmosphere and salt transport through the sea will be examined as part of a study of the paleooceanographic record in the northern Atlantic.

Results to Date. We now have in the LDGO computer the full set of GEOSECS, TTO, TAS, and SAVE data. Also available is the global topographic data set. We have worked over the nutrient, total CO_2, and alkalinity data with an eye toward uncovering calibration offsets between legs of a single expedition and between expeditions. We are confident that we now have a self-consistent data set for the entire ocean (except for the Pacific Ocean north of Hawaii). This data set can be displayed in geographic-depth or in geographic-isopycnal coordinates.

Maps of the global water budget have also been developed, and core analyses have been conducted to document the timing of glacial termination. Studies of the Atlantic Ocean circulation have led to papers on the distribution of radiocarbon ages and oxygen deficiencies in the deep Atlantic and on the impact of temporal changes in atmospheric ΔC^{14} on radiocarbon-based ventilation rates for the deep Atlantic and of the source waters for NADW.

Using the GEOSECS tritium and radiocarbon results as constraints, we have concluded that, even if iron fertilization drew the nutrient content of Antarctic surface waters down to zero during the months of sunlight, little reduction of the atmosphere's CO_2 content would occur. The surface waters of the Antarctic are replaced too slowly. Instead of the Antarctic drawing down the CO_2 content of the atmosphere (and non-Antarctic upper ocean), CO_2 transferred to the Antarctic from these other reservoirs would raise the pCO_2 partial pressure in Antarctic surface waters to nearly the prefertilization value.

Analyses of cores from the Red Sea and Antarctic Ocean have been examined to determine the timing and abruptness of the glacial termination. The major change seems to have occurred 12,800 years ago.

The freshwater balances of the GISS and Hamburg GCMs are being evaluated for present, doubled CO_2, and glacial conditions to better understand the potential for changes in Atlantic Ocean circulation.

RESEARCH PROJECT ON CO_2-INDUCED CLIMATE CHANGE

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

STATE UNIVERSITY OF NEW YORK, STONY BROOK

FY 1991	419
FY 1990	372
FY 1989	513

03/01/91-02/28/92

Objective. To intercompare GCMs, documenting physical processes responsible for agreement and disagreement, and to statistically analyze regional climate data sets for relationships between large-scale and regional climate.

Product. An understanding of the GCMs' abilities to represent large-scale climate and of the relationships between large-scale climate and regional climate.

Approach. GCMs' indications on CO_2-induced climatic warming will be intercompared model-to-model and model-to-data. The effort will involve 18 GCMs from throughout the world. An experimental protocol will be applied to the model-to-model comparison with a $\pm 2^{\circ}C$ sea surface temperature change as the forcing mechanism. The approach will assist in diagnosing cloud feedback and cloud forcing and the interactions of ice/snow albedo feedback and clouds in GCMs as a probable cause for GCM disagreements. CO_2 initial forcing and surface radiative balance will also be investigated.

To understand the natural variability in climatic parameters, subseasonal, annual, and interannual variations in air temperature, precipitation, and other observed climate parameters will be analyzed and compared with their simulations in GCMs. Through this process, the deficiencies of the models will be quantitatively ascertained, and their regimes of success will be demonstrated. Climatic data developed by the National Climatic Data Center in the United States and the Institute of Geography of the Chinese Academy of Sciences will be used in this project.

The two tasks on model intercomparison and natural climatic variability will be brought together to guide the estimation of regional climate change.

Results to Date. An investigation comparing the feedback between snow cover and climate in 17 GCMs has been completed. The results show that the traditional explanation of the feedback as simply an albedo change is incomplete because cloud redistribution plays a major role in modulating the interaction between climate and snow cover. Primarily because of difficulties in modeling clouds, the snow feedback differed markedly among the 17 GCMs. In a separate study, surface energy budgets have been compared among the models.

Further diagnostic studies have probed the capabilities of the GCMs in simulating regional climates. We have found that the OSU coupled ocean-atmosphere GCM simulates two major modes of variations in the Northern Hemisphere, the North Atlantic Oscillation and the North Pacific Oscillations. Comparisons with observations showed that the GCM reproduced the north-south pressure see-saws in the Atlantic and Pacific oceans that characterize the winter climates of these regions. The model was also shown to calculate many of the observed tele-connections of these oscillations in precipitation, air temperature, and sea surface temperature.

WORKSHOP ON RECONSTRUCTION OF SPATIAL PATTERNS OF CLIMATIC ANOMALIES DURING THE MEDIEVAL WARM PERIOD (A.D. 900-1300)

DIAZ, HENRY F., and HUGHES, M. K.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

FY 1991	16
FY 1990	0
FY 1989	0

01/01/91-03/31/92

Objective. To hold a conference on reconstructing spatial patterns of climate anomalies during the Medieval Warming, 900-1300 A.D.

Product. Essential data against which to test climate models and to establish ranges of natural climate variability.

Approach. DOE, in cooperation with the National Science Foundation and the National Oceanic and Atmospheric Administration, will bring together a select group of experts to evaluate four questions that define the utility of the Medieval Warming (900-1300 A.D.) data and that follow from the IGBP core activity goals:

- Were the Medieval Warming and the Little Ice Age global events?
- Were the responses synchronous, and the amplitudes comparable, in the northern and southern hemispheres?
- What were the relevant forcing mechanisms?
- What quantitative paleoenvironmental information is recorded in various natural proxy data?

Addressing these questions will set the stage for determining if quantitative spatial data can be developed and causal mechanisms defined.

SUPPORT OF MODELING ACTIVITIES UNDER THE WORKING GROUP VIII

ETKINS, ROBERT

NATIONAL CLIMATE PROGRAM OFFICE

FY 1991	19
FY 1990	0
FY 1989	0

09/15/91-09/14/92

Objective. To support some of the modeling activities to be conducted in conjunction with the next Working Group VIII annual meeting.

Product. Improved model cloudiness parameterizations, model development, collection of necessary data and methods of analysis, and GCM intercomparisons.

Approach. Working Group VIII is part of the US-USSR Joint Committee on Cooperation in the Field of Environmental Protection. Its annual meeting, to be held in late October 1991 and hosted by the National Climate Program Office, will review current activities and plan the program for the following year. Joint studies in modeling between U.S. and USSR specialists will be conducted at several U.S. locations during 1991. Subjects to be covered include international GCM intercomparison, comparison of model-simulated cloudiness with observed data, and greenhouse-O_3-marine productivity interaction.

PROGRAM FOR CLIMATE MODEL DIAGNOSIS AND INTERCOMPARISON

GATES, W. LAWRENCE

LAWRENCE LIVERMORE NATIONAL LABORATORY

FY 1991	3191
FY 1990	3162
FY 1989	2000

10/01/90-09/30/91

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

Product. A systematic basis for the improvement of GCMs and an ability to study variables of particular interest to those conducting studies of the possible impacts of climate changes.

Approach. Major issues to be addressed by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) are model resolution, the climate sensitivity to model parameterizations, and climate predictability. We will initially study these issues with the European Centre for Medium Range Weather Forecasts (ECMWF) operational model, which is

recognized as among the best in the world for weather forecasting. It can be run at T-21, T-42, T-63, T-106 and T-213 (spanning 6^{o} to 0.5^{o} latitude grids). Parallel with a resolution study, diagnostic packages will be developed to estimate the structure and distribution of systematic errors and their relationship to the model's parameterized physical processes. Particular attention will be given to the diagnosis of the surface heat and hydrologic balance, of cloud-radiative forcing, and of low-frequency variability. A data bank for systematic model validation and a comprehensive inventory of model properties will also be developed.

Results to Date. In year-long integrations of the ECMWF model at T-21, T-42, T-63, and T-106 resolutions with the same climatological sea-surface temperatures, the large-scale seasonal distributions of the mean atmospheric pressure, temperature, circulation, and precipitation show relatively little reduction of error with resolutions higher than T-42 (about 3^{o} latitude), although significant changes occur in higher-moment statistics. Analysis of the cloud radiative forcing in these and other experiments shows similar results when the forcing is calculated by the "on" and "off" method, but validation against ERBE observation is made difficult by the complexity of the ERBE data-reduction algorithm.

Significant progress has been made in the development of portable computer software for the storage and retrieval of large volumes of model (and observational) data sets and for the interactive visualization of model results.

A notable programmatic accomplishment is the successful launch coordination and support of the internationally coordinated Atmospheric Model Intercomparison Project (AMIP), which calls for simulation of the period 1979-1988 under standard conditions and the calculation of standard output. This project will permit model validation in unprecedented detail and a wide variety of diagnostic studies of model performance.

A RESEARCH PROGRAM ON NATURAL AND ANTHROPOGENIC CLIMATE CHANGE

GUTOWSKI, WILLIAM J.

ATMOSPHERIC AND ENVIRONMENTAL RESEARCH, INC.

FY 1991	429
FY 1990	408
FY 1989	394

03/01/91-02/28/92

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

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

Approach. The causes for the differences between the spectral and grid-point numeric formulations will be investigated to see if the moisture field and the moisture fluxes are different between 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 to assess the ability to use GCM results as the boundary conditions for a mesoscale model to further improve the representation of regional climate. And the atmospheric energy budget components associated with atmospheric moisture and clouds (including the horizontal and vertical latent and sensible heat fluxes, thermal and solar radiation, and heat storage) will be analyzed to assist in identifying the physical processes that cause the model differences.

Climate data, including paleoclimate data from the People's Republic of China for 6000 years

B.P., will be analyzed and used to evaluate statistics from several climate models against the observed climate. That the U.S. climate is essentially monsoon free and the Chinese climate is dominated by the monsoon is important for model validation. For example, the timing of the monsoon, which is known to within a few days in the historical record, can be used as a climate parameter to test the models. The same statistical analyses conducted on the data will be conducted on the model results, and the observed climate will be compared to the model climates. The physical causes of arid/semiarid climate in the USA and China and how the areas defined as arid/semiarid regions may change as CO_2-induced climate change will be investigated.

The scientific coordination of the USA-DOE/PRC-CAS joint research project on CO_2-induced climate change will be assisted.

Results to Date. The usefulness of the NCAR CCM1 and the NCAR/Penn State MM4 models in studying regional climate changes was assessed. Comparisons of GCM-simulated dynamical fields and their changes upon a doubling of CO_2 were performed. The GCMs examined indicated that atmospheric angular momentum, and hence the length of day, could decrease measurably from CO_2 doubling. Regional analysis of standing-wave eddy activity indicates that wave activity flux from the midlatitudes into the subtropics by stationary patterns would decrease when CO_2 doubles, thus affecting the meridional propagation of energy and moisture into regions impacted by standing-wave fluxes.

The Chinese monsoon's seasonal and latitudinal changes have been studied, with an aim of understanding how climate changes might affect monsoons. Analysis of urbanization effects on historical temperature records for China has shown that temperature records are clearly affected by human growth around measurement stations, but no clear trend with population can be identified.

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

GUTOWSKI, WILLIAM J.

ATMOSPHERIC AND ENVIRONMENTAL RESEARCH, INC.

FY 1991	219
FY 1990	207
FY 1989	199

09/01/91-08/31/92

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 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 and 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, separate from CO_2 alone, may modify the initial radiative heating/cooling profile in the atmosphere will be examined. The combined effects in a GCM experiment will assist in understanding and defining the predicted climate response. To assist in the analysis of the GCM experiment and to examine meridional heat transport feedback mechanism, the seasonal energy balance model will be further developed and applied. Adding a stratospheric photochemical model will expand the research to include the effect of

stratospheric temperature changes on surface temperature.

Results to Date. The initial phase of line-by-line computations of radiative fluxes and heating rates to study effects of the water-vapor continuum has been completed with output compared to other ICRCCM line-by-line results. Computations have been used to assess the numerical requirements for attaining an accuracy within 5%, the accuracy of the input physical data. Improved water-vapor-continuum data have been included in the Wang parameterization of longwave radiation. Effects of the improved data on radiation budgets are being analyzed.

The study of the effects of trace gases other than CO_2 has been completed. The spatial distribution of atmospheric opacity is different between CO_2 and other trace gases, which leads to different radiative forcings. The results indicated that the radiative effects of trace gases cannot be represented by an effective CO_2 amount and, hence, must be treated explicitly in global climate models. The seasonal energy balance model that has been developed to assist GCM analysis has been improved with the addition of a thermodynamic sea-ice model. The updated model has been used to study effects of seasonality and dynamic feedback on the stability of the Earth's climate.

DATA PREPARATION AND ANALYSIS FOR ANNEX III, USA/PRC COOPERATION IN THE FIELD OF ATMOSPHERIC TRACE GASES

KARL, THOMAS R.

NATIONAL CLIMATIC DATA CENTER

FY 1991	253
FY 1990	209
FY 1989	0

03/15/91-03/14/92

Objective. To develop comprehensive regional climate reference data sets and to quantify and understand regional climate change in the United States and China by using both observations and general-circulation model (GCM) calculations (model control climates).

Product. A regional climate data set that can be used as a primary reference for understanding climate change and testing of GCMs.

Approach. In examining regional climate sets, changes in any single climate element (e.g., surface temperature) must be understood in the context of changes in the rest of the climate system. Furthermore, annual and seasonal statistics of a specific element are insufficient for detection of climate change. Compilation of comprehensive data sets (on a regional basis) are required, including information on surface quantities (such as precipitation, moisture, temperature, and snow cover) as well as information on clouds, temperature, moisture, pressure, and wind above the surface.

The NCDC will provide a regional data set for the contiguous USA and Alaska. The Alaskan data are included because the GCMs predict large and early changes in the polar regions. Climate statistics will be derived from the regional climate reference data sets and will be analyzed in context with GCM equilibrium and perturbed experiments.

The Climatological Prediction by Model Statistics (CPMS) will be developed, the model results will be tested against the observations, and the changes in the CPMS as CO_2 is increased in the model will be examined. Model fields will be compared to observations, including the diurnal temperature range, upper atmospheric variables (e.g., temperature and pressure height), and multidimensional analysis of surface and upper-air variables. Concomitant changes in snow depth and temperature will be studied to determine any long-term evidence for early spring snowmelt, and the improved Alaskan data set will be examined for changes. Any urban

heat island in China will be quantified, a key element because the scientific basis for using the U.S. urban heat island to estimate urban effects on the global data set is not established.

Results to Date. Experiments with CPMS indicated that even an early version of the OSU GCM can produce free-atmosphere statistics that can closely approximate the local surface climate. CPMS and additional statistics were then used to examine the performance of a recent version of the National Center for Atmospheric Research Community Climate Model. Persistence (day-to-day changes) in the model was examined.

The possibility of a discontinuity in the U.S. Cooperative Network by the introduction in the 1980s of the Maximum/Minimum Thermometer System (MMTS) was examined. Results indicate that the average bias by changing from a Cotton Region Shelter to the MMTS was a lowering of the monthly maximum by approximately 0.4° C and a rise in the monthly minimum by approximately 0.3° C.

The possible linkage between coral bleaching in the Caribbean Sea and climate was examined using Sea-Surface Temperatures and Historical Climatology Network (HCN) data. No convincing link between climate and coral bleaching was found.

Trends in both maximum and minimum temperatures for the U.S., the Peoples Republic of China, and the Soviet Union indicate that, although the maximum temperature has increased slowly in all three countries, a much larger increase occurs in the minimum, causing a decrease in the diurnal temperature range.

A numeric data package of historic cloud and sunshine data was prepared for and published by the Carbon Dioxide Information and Analysis Center.

Analyses and text were contributed to the report *Policy Implications of Greenhouse Warming Effects Panel* published by the NAS-NRC Committee on Science, Engineering, and Public Policy.

CLIMATOLOGICAL AEROLOGICAL (UPPER-AIR) REFERENCE DATA SET (CARDS)

KARL, THOMAS R.

NATIONAL CLIMATIC DATA CENTER

FY 1991	632
FY 1990	225
FY 1989	0

07/01/91-06/30/92

Objective. To build a Climatological Aerological (Upper Air) Reference Data Set (CARDS) from the radiosonde data archives.

Product. A key data set for climate research requiring atmospheric profiles of temperature, winds, and humidity.

Approach. The data consist of temperature, pressure, wind velocity, and humidity profiles of the atmosphere. Such data have been measure from twice-daily balloon launches at 700 to 800 sites around the globe for about 50 years. However, the data are subject to many biases, including the effects of solar radiation on the temperature and humidity sensors. Early data are often uncertain and require extensive correction.

A global data set of daily upper-air and concomitant surface synoptic observations will be produced from various collections of upper-air and colocated surface observations. The most extensive data set possible will be collected. A suite of programs will be developed to correct for random errors and outliers. These data sets have not been quality controlled in a systematic manner. The procedures will include a range of methods from statistical to physical (impossible temperatures, pressures, etc.). Suspect stations have been noted by the U.S. and European

weather centers. This list will assist the task. The homogeneity of the data from the upper-air network will be assessed, and corrections for biases will be implemented where appropriate. The station histories provide the information necessary to correct for known biases for sensor and methodology changes and differences over time and between stations. These data will be analyzed with basic climate-change-analysis schemes to help ensure against undetected errors and biases and to provide complete documentation. A modest operational program will be instituted to ensure the integrity of future data. These data sets will be made readily available via the Carbon Dioxide Information and Analysis Center.

Results to Date. The CARDS project has been subdivided into four components: data-set integration, random-error edits, systematic-error edits, and a system for data base updates. To date, a nucleus of data sets has been identified and incorporated into a network of Sun work-stations. These data sets include National Meteorological Center collectives, U.S. Air Force data gathered by the Massachusetts Institute of Technology, special collections of USSR data, and several national collections. Additional requests for data have been forwarded to 38 foreign national data centers for supplemental national and regional data. Data and positive responses to contribute data have been received from several countries, including the USSR and the PRC.

A CARDS station history format has been developed and several existing digital histories are being converted and integrated into this format. Station histories are also being solicited through the WMO. These are being converted into a digital file and incorporated into the station history data base.

The U.S. National Weather Service's operational Complex Quality Control Program for upper-air data has been modified to operate in a climate mode. This program will be one of several random-error edits.

RECENT CHANGES OF WEATHER PATTERNS IN NORTH AMERICA

KUKLA, GEORGE, AND KARL, TOM

COLUMBIA UNIVERSITY and NATIONAL CLIMATIC DATA CENTER

FY 1991	1>2
FY 1990	185
FY 1989	183

08/15/91-08/14/92

Objective. To develop the data sets needed to evaluate changes in the properties and frequencies of air masses and extreme weather events over North America and to compare any observed changes to climate-model predictions of greenhouse-gas- and aerosol-induced climate change.

Product. Data that will address climate variability (which complicates the detection of climate change) and changes in climate variability and extreme weather events (which are key variables in assessing the impacts of any future climate change).

Approach. Surface and upper-air data bases from the National Climatic Data Center and from other ongoing DOE research will be used to develop the air-mass and extreme-event data sets. As the study progresses, data from China and the USSR will be used to extend the results to the Northern Hemisphere.

The air-mass types will be define primarily on humidity and free atmosphere wind direction. Each type will be characterized and analyzed on weather events, temperature, cloud fraction, etc. The frequency of air-mass-type changes will be analyzed for relationships to warm/cold years and El Niño/La Niña years. The variability and changes within air-mass type will be documented. The temperature and precipitation extremes within an air mass will be analyzed along with the time-related changes. The results of the

above analyses will be compared to climate calculations.

Results to Date. We continued analyzing asymmetric changes in the mean, maximum, minimum, and extreme temperatures over the United States in the past decades. We expanded the study to include the USSR and China, for which we recently obtained data. Virtually all of the warming observed in these countries is caused by the increase of night temperatures with little change in the maximum. Increased cloudiness caused at least a part of the difference.

With the NCAR climate modelers, we compared temperature anomalies of the past 40 years in the Northern Hemisphere with the model. We found a close correspondence with the NCAR model projection in which the CO_2 gradually increases by 1% annually for 30 years. Although the geographic distribution of observed anomalies resembles the model, the link with the rise in CO_2 is uncertain because of the large variability seen in the observations and the model.

We have also tried to further reduce the uncertainties associated with documenting climate change. We have found that precipitation discontinuities are so large and one-sided during the period of frozen precipitation that any time series from these areas must be considered tentative at best.

CARBON DIOXIDE EFFECTS RESEARCH

MacCRACKEN, MICHAEL C.

LAWRENCE LIVERMORE NATIONAL LABORATORY

FY 1991	988
FY 1990	1085
FY 1989	970

10/01/90-09/30/91

Task I. Model Intercomparison (G. Potter)

Objective. To sharpen estimates of future climate change that might occur as a result of energy-related activities (particularly those that are increasing the atmospheric concentration of carbon dioxide) by determining the rate of climate change in response to prescribed radiative perturbations and by increasing understanding of the cloud feedback effects, which are uncertain but undoubtedly important in determining overall climate sensitivity.

Product. Improved understanding of the factors that determine the rate of climate change and the processes that determine climate sensitivity, including cloud radiative feedback effects; maintenance and enhancement of current models of the atmosphere (both 2-D zonally averaged models and 3-D general-circulation models); and ocean modeling capabilities.

Approach. This research will build on tools that have been developed at LLNL and other research centers during the past decade. In particular, 3-D atmospheric-circulation models (two versions of the CCM) along with a 2-D atmospheric-circulation model (recently developed at LLNL) will be used to study issues of climate sensitivity and feedbacks. For studying the transient behavior of the climate system, two global ocean models have been adapted to the LLNL computer system, an isopycnal coordinate model developed by Oberhuber and Semtner and Chervin's more traditionally formulated model.

The comprehensive GCMs will be used to analyze in detail the relative importance of the various processes and feedbacks that contribute to the spatial and seasonal sensitivity of climate to radiative perturbations similar to those expected from an increase in atmospheric carbon dioxide. The zonally averaged model and simplified models of individual processes will then be used to assist in analyzing and interpreting results. They can also be used in exploratory studies to help determine which lines

of research are likely to be most fruitful with the GCMs. Where possible, results will be compared with observations.

Results to Date. The strength of cloud liquid water feedback as simulated by a general circulation model (the Livermore version of the Community Climate Model, CCM/LLNL) has been studied. We found that under an idealized global-warming scenario, feedbacks associated with changes in cloud amount, cloud liquid water content, and cloud distribution (especially in the vertical) are all of comparable importance, but with partial compensation between positive and negative effects.

The effects of snow feedback in the CCM/LLNL model have also been studied, and results from many GCMs have been intercompared. In addition, we have nearly finished modifying an atmosphere-ocean 2-D climate model developed at New York University and Toronto University, which will initially be used to test a procedure for intercomparing ocean GCMs.

Task II. 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; to assist in providing technical evaluation and coordination of the climate research component of the DOE CO_2 research program and in integration of the research program; to foster graduate and postdoctoral education through sponsorship of collaborative research within the University of California system of campuses and laboratories; and to sponsor special enabling research to assist the DOE Carbon Dioxide Research Program enhance model intercomparison studies.

Product. A DOE focal point for climate research undertaken by federal and international climate programs relevant to the CO_2 clir te issue; specific studies on timely CO_2-climate sues; and statistical-analysis support for activities, such as overviews of model/data comparisons.

Approach. To assist the DOE Carbon Dioxide Research Office in areas of projection and detection of climate change, Dr. Michael MacCracken will serve as a principal scientific advisor for climate research, assisted by LLNL staff. In this role, he will assist in formulation and implementation of the research program, review of research proposals and scientific literature, preparation of progress reports, planning of meetings, and communication with the scientific community. Under DOE guidance, LLNL will subcontract other investigators to initiate studies in innovative technical areas and will coordinate intercomparison efforts and reviews to help resolve differences in results and identify uncertainties.

Results to Date. Two major reports were published (for DOE, *Energy and Climate Change*; for US/USSR, *Prospects for Future Climate*) and substantial effort was extended to the IPCC assessment. A report describing what is agreed upon and listing ten key uncertainties was prepared to support of DOE's preparation for international negotiations on a climate convention.

As a member of the National Academy of Sciences subpanel on climate effects, input was prepared that compared the relative importance of various greenhouse gases. A report was prepared for the NIGEC conference on engineering solutions to the greenhouse effect reviewing approaches for geoengineering the climate.

Support was provided for postdoctoral and graduate fellowships at Scripps, UCLA, and U.C. Davis through the University of California Institutional Collaborative Research program. Support is provided to W. Broecker at Lamont-Doherty Geological Observatory through a subcontract to develop tracer and other tests that can be used in ocean-model verification studies.

Task III. Global Climate Change Curriculum Development (M. Perry)

Objective. To provide elementary, middle, and high school teachers with the support necessary to develop effective, interdisciplinary instructional materials for addressing issues related to the problem of carbon dioxide buildup in the Earth's atmosphere.

Product. Development and dissemination of curriculum materials on global climate change stressing the interdisciplinary nature of the issues, but with primary focus on the relevant scientific aspects.

Approach. Teachers in the Livermore region, in the northern California area, and in the southern California region will participate in a series of 13-day training programs. The funding will provide for three teachers' salaries, stipends for 100 teachers in the workshops, all equipment and materials, and travel to northern and southern California to conduct the workshops. By bringing together teachers of both scientific and nonscientific disciplines to focus on a problem of international concern, this program will create a setting in which the sciences are seen as relevant and beneficial to humanity. It will also inspire a valuable partnership between the scientific and educational communities.

In addition, the middle school curriculum, developed in 1990, will be disseminated to regional teachers in one 13-day summer workshop. Work will continue on the middle school component of the curriculum. Funding provides for 5 teachers in the curriculum development, stipends for 20 teachers in the one 13-day workshop, and all equipment and materials.

Finally, six new teachers from the elementary-school level will begin the development of the elementary level curriculum. Funding provides for the salaries of these teachers.

Results to Date. During the summer, the high school component of The Greenhouse Effect and Global Climate Change curriculum project successfully instructed 80 secondary teachers on the use of the materials. The teachers who wrote the curriculum, representing the subject areas of science, social science, and language arts, modeled the team-teaching approach for this interdisciplinary unit in four 1-week workshops in Hayward, Sacramento, Stockton, and San Bernardino. Workshop participants received the curriculum binder that had been revised based on input from both last summer's participants and from the DOE committee that reviewed the curriculum materials in the winter of 1990/1991. Participants also received kits containing all laboratory materials and a class set of the reading text and exams. Workshop teachers were placed in cooperative learning teams that performed the curriculum's laboratory activities. The quality of the workshops was enhanced further by discussions with LLNL scientists.

Six teachers (three science, two math, and one social studies) have begun testing the interdisciplinary-curriculum materials in the classroom. Three new elementary-school teachers were hired, and they have started developing curriculum at the elementary level. Course designs have been completed, and lesson plans are being developed.

FIELD, LABORATORY, AND MODELING STUDIES OF WATER INFILTRATION AND RUNOFF IN SUBFREEZING SNOW ON REGIONAL SCALES TO ESTIMATE FUTURE GREENHOUSE-INDUCED CHANGES IN SEA LEVEL

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

INSTITUTE OF ARCTIC AND ALPINE RESEARCH

FY 1991	192
FY 1990	202
FY 1989	0

07/15/91-09/14/92

Objective. To forecast future sea-level change caused by greenhouse-induced changes in runoff from polar glaciers and ice caps.

Product. A model to predict the development of impermeable firn (and consequent runoff and discharge to the ocean) in response to predicted future climate change.

Approach. The processes of infiltration and refreezing, which lead to the formation of impermeable firn layers, will be observed in the field. These observed processes will be reproduced in the laboratory to confirm and further quantify understanding. A regional-scale numeric model that can simulate these processes, based on measured parameters and driven by boundary conditions determined by climate, will be developed and calibrated. This model will be applied to predict the development of impermeable firn (and consequent runoff and discharge to the ocean) in response to predicted future climate change.

Results to Date. A local-scale numeric model was developed and tested. This 2-D model treats meltwater infiltration and refreezing in a layered snowpack, including realistic treatment of heat conduction, phase change, and fluid flow in the snow, with moving boundaries (freezing/subfreezing) and heat or water inputs at the surface that vary in both space and time. It has been applied to arctic snowpacks measured in the field.

At the other end of the spatial scale, a model was developed to estimate the retention of meltwater in the Greenland Ice Sheet. This describes how infiltration, refreezing, and runoff can be estimated based on two simple assumptions. Using a typical scenario for greenhouse warming (+4°C and +10% precipitation), this model predicts runoff for the area above the present runoff limit to be 4.0 to 4.3 cm (in global sea-level equivalent) less than would be predicted without refreezing.

PARTIAL SUPPORT FOR THE NAS BOARD ON ATMOSPHERIC SCIENCES AND CLIMATE

PERRY, JOHN S.

NATIONAL ACADEMY OF SCIENCES

FY 1991	50
FY 1990	0
FY 1989	0

03/15/91-03/14/92

Objective. To provide scientific leadership and guidance to the government on important national and international issues in the atmospheric sciences and climate.

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. The Board on Atmospheric Sciences and Climate (BASC) will provide scientific leadership and guidance to the government on important national and international issues in the atmospheric sciences and climate and on the coordination between discipline-oriented activities within the atmospheric sciences and interdisciplinary programs, such as the International Geosphere-Biosphere Program (IGBP). It will continue the activities of the Climate Research Committee (CRC) and, under the CRC, the Tropical Ocean-Global Atmosphere (TOGA) and International Satellite Cloud Climatology Project (ISCCP) advisory panels in providing guidance on U.S. participation in the World Climate Research Program and on TOGA, ISCCP, WOCE, and other WCRP activities and on related national climate research activities. It will continue the activities of the Committee on Atmospheric Chemistry, which will continue to focus its efforts on issues raised by contemporary atmospheric changes, such as increases in

greenhouse gases, stratospheric ozone depletion, and acid deposition. And it will maintain a capability to respond rapidly and effectively to requests by federal agencies and Congress for evaluations, guidance, recommendations, and support in the areas of atmospheric science and climate.

SENSITIVITY OF CLIMATE MODELS: COMPARISON OF SIMULATED AND OBSERVED PATTERNS FOR PAST CLIMATES

PRELL, W. L.; WEBB, THOMPSON, III; and OGLESBY, R. J.

BROWN UNIVERSITY

FY 1991	400
FY 1990	419
FY 1989	420

02/01/91-01/31/92

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

Product. A complete comparison between paleoclimate data and the NCAR GCM.

Approach. General-circulation models will be used to simulate a series of climatic changes from the past, assembled paleoclimatic data from large areas of the tropics and the northern hemisphere mid-to-high latitudes will be provided for the comparison of model simulations and observations, methods and procedures for improving the comparability of the observed and simulated data will be developed, and the model results will be compared with the paleoclimatic data. The COHMAP book will be completed.

Results to Date. No results reported.

THE ROLE OF CLOUDS IN CO_2-INDUCED CLIMATE CHANGE

RANDALL, DAVID A.

COLORADO STATE UNIVERSITY

FY 1991	175
FY 1990	169
FY 1989	109

09/15/91-09/14/92

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/atmospheric GCM.

Product. An understanding of the surface radiative forcings (relative to clouds) from the various GCMs, a comparison of the models with the available observations, and possible methodological short-comings; and an improved GCM with fully coupled ocean and atmosphere.

Approach. The radiative role of clouds in current climate and in a climate modified by increased atmospheric concentrations of CO_2 will be studied. To diagnose the differences among the GCMs and provide for improved physical parameterization of clouds, 14 GCMs will be compared on:

- surface fluxes (sensible heat, latent heat, infrared, and solar);
- precipitable water content; and
- precipitation and evaporation.

Differing cloudiness parameterizations will be studied in a simple coupled ocean/atmosphere model as atmospheric CO_2 concentrations change in order to guide and assist in understanding the effect of these modifications to the cloudiness schemes when used in the GCMs. Cloud data from satellites, aircraft, and balloons will be used to quantify cloud forcing and feedback processes as observed.

The Q-flux version of the ocean model will be developed, and an ocean GCM will be added to the existing CSU atmospheric GCM. The mechanics are simple; however, coupled GCMs magnify the imperfect 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.

Results to Date. Our study of the CO_2 forcing using the CSU GCM has been completed. The Q-flux ocean model, including a simple sea-ice parameterization is now being run in a fully coupled mode. The current coupled simulation is intended to serve as a "control" for a 2 x CO_2 simulation. A 10-year simulation using observed sea surface temperatures and sea-ice patterns was completed in support of the PCMDI model intercomparison. Ours was the first model to successfully complete this objective. The "snow feedback" simulations were completed. And considerable time and effort was invested in the planning of ARM.

METHANE FLUXES FROM RICE FIELDS IN CHINA: SPATIAL AND TEMPORAL VARIABILITY AND ESTIMATES OF CONTRIBUTIONS TO THE GLOBAL BUDGET

RASMUSSEN, R. A., and KHALIL, M. A. K.

OREGON GRADUATE CENTER

FY 1991	330
FY 1990	297
FY 1989	302

02/01/91-01/31/92

Objective. To measure the magnitude of the methane emission from rice-paddy fields.

Product. Data on the magnitude of methane emissions from rice-paddy fields, including seasonal and geographic characteristics.

Approach. The Oregon Graduate Institute will cooperate with the Chinese Academy of Science (Institute of Atmospheric Physics) to measure the methane release to the atmosphere from rice-paddy fields with a measurement approach that has been reviewed and tested extensively in field for the past 25 years. Basically, an enclosure will be placed over the plants, and a sample will be taken quickly with little or no disruption to the plant or the surrounding surface. Air and soil temperature, growth stage, soil type, fertilizer type, farming practice, etc. will be recorded.

The baseline effort at Tu Zu will provide a six-year base of measurements that can be compared to data taken at other locations. These additional sites will be selected to investigate spatial variability from different climate zones, soil types, farming practices, and rice varieties. The data, along with other methane-budget data, will be used to estimate seasonal variations and geographic variations in the global methane budget. Further, a midcontinental background site will be re-established to help assess the atmospheric concentrations of methane and other trace gases.

Results to Date. The factors that have been identified as controlling methane emissions are the soil and ambient temperatures, fertilizer use, type of rice, and the season in which rice is grown.

The study so far has shown that, on average, Chinese rice fields emit about 10 times as much methane during the growing season as do comparable fields in the U.S. and Europe. The global emissions of methane from rice fields, although not accurately known at present, are likely to be around 100 Tg/year or about 20% of the total emissions from all sources. Fields with hybrid rice emit much more methane than nearby fields with regular rice. If this preliminary finding is sustained after our detailed analysis, it would be the most important finding of the experiment to date. Rice agriculture all over the world is shifting to planting more and more high-

yield hybrid rice, which could greatly increase atmospheric methane even though no new rice areas are being planted.

VOLCANIC SIGNAL IN GLOBAL CHANGE

ROBOCK, ALAN

UNIVERSITY OF MARYLAND

FY 1991	50
FY 1990	50
FY 1989	0

06/15/91-06/14/92

Objective. To develop an improved volcanic index for climate analysis and to analyze the observed climate record (surface temperature) for evidence of volcanic-induced cooling, including comparison with GCM calculations.

Product. An improved volcanic index for climate studies.

Approach. The existing volcanic indices suffer major flaws. A new index will be developed based on solar radiation data, atmospheric turbidity data, ice core chemical analyses, the brightness of standard reference stars (which yields a measure of atmospheric turbidity), and satellite data as well as on examinations of the existing volcanic indices. This new index will establish a time series for use with climate models (ideally, an estimate of atmospheric aerosol concentrations).

The surface-temperature record of the past 150 years will be analyzed and compared to the newly developed volcanic index. The resultant information is expected to provide a clearer understanding of the relationship between natural variability of the climate and causative mechanisms, such as volcanic activity.

The GCM analysis will be conducted to further assess cause and effect. The analysis will be initiated as appropriate as the study progresses.

Results to Date. Work has progressed in three areas: development of an improved volcanic index, comparison of the surface temperature record to the volcanic record, and GCM modeling of volcanic eruptions. We have obtained annual ice-core records for four cores and compared them to the Lamb/Mitchell DVI. We are in the process of adding more ice cores and radiation and astronomical data to the analysis. In correlating the surface temperature to the DVI, we find negative correlations for two years following eruptions in the tropics, indicating a cooling signal. We have analyzed the GCM experiments of Hansen and found a large temperature signal but no El Niño signal. We are currently conducting GCM experiments with the CCM1 on the Livermore computer system.

GREENHOUSE-GAS-INDUCED CLIMATE CHANGE

SCHLESINGER, MICHAEL E.

UNIVERSITY OF ILLINOIS

FY 1991	130
FY 1990	140
FY 1989	0

06/15/91-06/14/92

Objective. To analyze the feedbacks in the CO_2-induced warmings simulated by the two-level model and the new multilevel model; to analyze the causes of the CO_2-induced drying in the Northern Hemisphere continents in the summer as simulated by the models; to analyze the CO_2-induced changes in the diurnal cycle simulated by the multilevel model; and to analyze the cloud optical feedbacks on CO_2-induced climate change.

Product. An increased understanding of the GCM feedbacks leading to an improved model of known capability.

Approach. The range of model feedbacks will be quantitatively determined as part of the overall DOE program of model diagnostics. A radiative-transfer-model developed previously will be used. To lay the basis for improvements in the soil-water modeling subcomponent of the GCM, the soil-water balance in the model will be quantitatively analyzed to determine the model mechanism.

To develop a basis for the detection of climate change, the model's diurnal cycle of temperature for 1 x CO_2 and 2 x CO_2 will be compared with observations that suggest that the diurnal range of temperature should decrease. The daily maximum is dominated by solar heating so the CO_2 should have little impact while the nighttime low may show a large impact of CO_2-warming (i.e., getting warmer) so the range decreases. Testing the model for this possible phenomena may provide a piece of a specific CO_2 fingerprint.

A transient model run will be conducted to provide a basis for the comparison with the observation over the past 100 years. To carry out this experiment, it will be necessary to verify the new ocean GCM. This will be done by comparing the observed ocean tracer data (e.g., the penetration of bomb tritium) with the model estimates of the trace distribution. Subsequently, the coupled model will be run with 1 x CO_2, with 2 x CO_2, and in a transient mode with slowly increasing greenhouse gases. The results will be intercompared as well as compared to the observed record of climate.

Recent GCM research has show that the model sensitivity can change by a factor of 2 when cloud optical properties are changed or calculated rather than prescribed. Research will continue to develop more physically based parameterizations for incorporation in the GCM. This will include a new boundary-layer parameterization.

Results to Date. Both our two-layer and multilayer atmospheric general-circulation (AGC) models were improved; and a coupled atmosphere-ocean-ice sheet-asthenosphere model, a radiative-convective model for the entire atmosphere, and a parameterization for the evaporation of clouds for use in AGC models were developed.

The present climate was simulated with our multilayer AGC model, and the climate evolution from 1765 to 2100 was simulated with our simple climate/ocean model. With our atmosphere-ocean-ice sheet-asthenosphere model, the climate evolution during the next 20,000 years and the onset of the last glacial from 115,000 to 105,000 years ago were simulated, the latter twice, by Milankovitch orbital forcing alone and by orbital forcing plus reduced CO_2.

The present climate was also simulated with a Soviet AGC/mixed-layer ocean (MLO) model. We analyzed the soil moisture simulated by our 2-layer AGC/MLO model with Soviet observations. The cloudiness simulated by six AGC models was intercompared and analyzed with satellite-based and ground-based cloudiness observations. We developed a representation of our coupled atmosphere/ocean GCM by a simple climate/ocean model, investigated the relative penetration into the ocean of passive tracers compared to the CO_2 heating simulated by our coupled atmosphere/ocean GCM, and compiled a climatology of sea-ice thickness and areal extent. The cause-and-effect analysis technique was developed, and it was applied to the determinations of the sensitivity and stability of geophysical models.

The books *Climate-Ocean Interaction* and *Greenhouse-Gas- Induced Climatic Change: A Critical Appraisal of Simulations and Observations* were published.

ENHANCED RESEARCH PROGRAM ON THE LONG-RANGE CLIMATIC EFFECTS OF INCREASING ATMOSPHERIC CO_2

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

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

FY 1991	364
FY 1990	409
FY 1989	0

06/01/91-05/31/92

Objective. To couple the enhanced atmospheric CCMO and CCM2 and the 1^{o} x 1^{o} dynamic ocean general-circulation model (GCM) and to perform a series of sensitivity experiments with the coupled and uncoupled models, including transient CO_2 experiments.

Product. A global coupled GCM capable of regional climate calculations.

Approach. A control run (1 x CO_2), an instantaneous 2 x CO_2 experiment, and a transient experiment will be performed. These experiments will be done with the enhanced atmospheric GCM (CCMO and CCM2). This set of experiments is necessary to benchmark the new version of the model against the previous results and, therefore, provides a basis for analyzing the experiments conducted with the advanced dynamic ocean.

The two advanced models will be coupled. The dynamic ocean model is a 1^{o} x 1^{o} version of the Semtner-Chervin $1/2^{o}$ x $1/2^{o}$ ocean model with 20 vertical levels. The 1^{o} x 1^{o} version of the Semtner-Chervin to be used in this research explicitly resolves some aspects of the mesoscale eddies as does the parent model, but research has shown that observed ocean features sufficient for climate experiments can be simulated without such a detailed explicit calculation. This hypothesis will be tested with the coupled model.

The coupling scheme will be synchronous rather than asynchronous. Asynchronous coupling does not allow for the time evolution of the interaction between the ocean and atmosphere. In the NCAR scheme, the atmospheric model provides wind stress, precipitation minus evaporation, and the sum of the surface energy balance to the ocean. The ocean provides surface temperature and sea-ice distribution to the atmosphere. The coupled experiment will be started from separate runs of the new models, each "forced" with the appropriate observed climate conditions (e.g., the observed sea surface temperature for the spinup of the atmospheric model). This will allow separate diagnosis of any model problems before coupling. The result will be the first coupled GCM experiments with a medium-resolution ocean model (1^{o} x1^{o}) sufficient to simulate primary ocean climatological features.

Results to Date. In a series of manuscripts, we have documented how the El Niño-Southern Oscillation operates in the model and how it is enhanced with increased carbon dioxide. Although not all aspects are well simulated, most major features are as shown in comparison with observations. In studies with collaborators Branstator, Karoly, and Karl, we have explored the possible carbon dioxide "fingerprint" in zonal mean temperatures, the effects of changes in extratropical teleconnections, and the regional effects of low-frequency variability and climate change. The latter is of special interest to policy makers because a separation is necessary between natural and anthropogenic change and variability.

An advanced version of the NCAR community climate model that includes the Ramanathan and Collins cirrus albedo feedback mechanism has been run with a mixed layer and has been tested with the 1^{o} 20-level Semtner and Chervin ocean model. The latter includes the Arctic Ocean and dynamic sea ice, both of which have shown realistic results. The model has been configured in a multitasking mode and will be coupled to the CCM2.

DETECTION OF CO_2-INDUCED CLIMATE CHANGE

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

UNIVERSITY OF EAST ANGLIA

FY 1991	118
FY 1990	111
FY 1989	121

12/01/90-11/30/91

Objective. To assemble and analyze instrumental climate data and to develop simple climate models as a basis for detecting greenhouse gas-induced climatic change and validating general-circulation models (GCMs).

Product. A high-quality, spatially extensive data base to define the noise of natural climatic variability and its spatial characteristics.

Approach. Available land and marine data bases will be updated and expanded, and differences between different data sets will be reconciled where possible. The data will be analyzed to determine the potential effects on climate of greenhouse gas concentration changes and other factors. Analyses will be guided by simple energy-balance climate models. Data analyses will focus on use and development of appropriate statistical techniques for signal detection and pattern recognition. These analyses are oriented towards obtaining early evidence of greenhouse gas-induced climatic change that would lead to confirmation, rejection or modification of model projections and towards the statistical validation of GCM control runs.

Results to Date. A combined land/marine temperature anomaly data set has been produced (1854 to present). This data set uses a new correction method for the *marine* data, which partially resolves earlier nineteenth-century differences with the U.K. Meteorological Office data. For the *land* data, regional-scale tests have shown that residual urban biases are minimal. Further work (using our upwelling-diffusion model) on man-made, fossil-fuel-derived SO_2 as a factor in climate change (through tropospheric sulphate aerosol changes) has reinforced our earlier suggestions of its importance. Over the twentieth century, SO_2 effects in the Northern Hemisphere may be comparable in magnitude (but opposite in sign) to the effects of greenhouse gases. Our simulations of internally-generated, low-frequency natural variability are very similar to those generated by coupled atmosphere-ocean GCMs. This process may lead to 100-year trends in global-mean temperature of up to 0.3°C. We have estimated the range of ΔT_{2x} values and found them to be consistent with the observed global mean warming of around 0.5°C during the past 100 years. The result, $0.8 \leq \Delta T_{2x} \leq 4.3$°C, overlaps with the GCM-based range of $1.5 \leq \Delta T_{2x} \leq 4.5$°C. Our models were used to predict global-mean temperature and sea level changes as part of the IPCC exercise. Our latest estimates for changes from 1990 to 2100 are: temperature, 1 to 7°C (best guess, 2.5°C); sea-level rise, 3 to 124 cm (best guess 46 cm).

TRACE-GAS INTERACTIONS IN THE GLOBAL ATMOSPHERE

WUEBBLES, DONALD J.

LAWRENCE LIVERMORE NATIONAL LABORATORY

FY 1991	205
FY 1990	346
FY 1989	250

10/01/90-09/30/91

Objective. To understand the effects that increasing atmospheric concentrations of CO_2 and other trace gases may be having on global atmospheric chemistry and climate; to understand the interactions among climate, chemical, and radiative processes; and 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 determination and evaluation of the mechanisms and processes reflecting the influence that trace gases may be having on the global environment; and an understanding of what measurements are required to further develop and validate global atmospheric models to study climate and chemical interactions.

Approach. These studies will (1) develop information on past trends and the potential for future increases in the concentrations of the various trace species, an effort being coordinated with studies of trace-species histories and economic analyses being done at PNL; (2) examine budgets of relevant trace gases to better establish which uncertainties require consideration in development of scenarios of future emissions; (3) extend existing capabilities for modeling global atmospheric chemical, radiative, and physical processes; (4) perform model-sensitivity analyses to better define the mechanisms, key parameters, and overall uncertainties of potential trace-gas influences on the atmosphere; and (5) establish a clearer relationship 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 will extend present modeling capabilities and develop 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 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 climatic models for use in interactive simulations.

Results to Date. The trends and budgets of greenhouse gases were reevaluated and updated from available observations. Wuebbles and Edmonds completed their book *Primer on Greenhouse Gases*. A chapter of another book (Wuebbles, 1991) concerning external forcing on climate change from greenhouse gases was completed. A chapter for a special report to Congress was completed in coordination with Edmonds and others.

The 2-D chemical-transport model was used to examine the influence of solar variations and trace-gas emissions on upper stratospheric ozone and temperature during the 1970s and 1980s. An examination of the radiative effects of observed changes in lower stratospheric ozone and carbon dioxide during the past two decades showed that these changes can largely explain the observed trends in lower stratospheric temperatures.

Wuebbles wrote a major section of a National Academy of Sciences report concerning solar influences on global change. He was also Panel Coordinator and lead author of a meeting and resulting book on *The Engineering Response to Global Change*.

CHAMMP Initiative

Research Summaries

DEVELOPMENT OF AN ADVANCED FINITE-DIFFERENCE ATMOSPHERIC GENERAL-CIRCULATION MODEL

ARAKAWA, A., and MECHOSO, C. R.

UNIVERSITY OF CALIFORNIA AT LOS ANGELES

FY 1991	121
FY 1990	0
FY 1989	0

09/01/91-08/31/92

Objective. To develop a higher-resolution finite-difference model with improved process parameterizations that is suitable for a massively parallel computing environment.

Product. Improved methods for describing physical processes in atmospheric and ocean general-circulation models (GCMs) and the development of these models on massively parallel computer systems to carry out climate-prediction studies.

Approach. A documented copy of the current model code will be made available to the CHAMMP science team investigators on a parallel supercomputer. As improvements to the model are made at CSU and UCLA, they will be transferred to the CHAMMP community. Improved physical parameterizations will be developed for cloud processes, convection, land surface exchange, and the planetary boundary layer based on information from recent observational programs and theoretical advances.

The computational framework of the model will be improved. Recent developments in more accurate numeric methods will be incorporated into the model so that it more faithfully simulates the real atmosphere, particularly in its representation of flow near the poles. These improved formulations will partially overcome the inaccuracies in finite-difference modeling that gave rise to the spectral models.

Sensitivity experiments will be run to test the improved parameterizations and methods as a function of model resolution. Models perform better at higher resolution because the process parameterizations are more faithful to the real world at finer spatial scales. These sensitivity tests will examine how well the parameterizations scale with different grid spacings.

CHAMMP DETAILEE ASSIGNMENT

BADER, DAVID C.

PACIFIC NORTHWEST LABORATORY

FY 1991	225
FY 1990	65
FY 1989	0

10/01/90-09/30/91

Objective. To provide a full-time atmospheric scientist familiar with large-scale computer modeling to help coordinate the early development of the Computer Hardware, Advanced Mathematics, and Model Physics (CHAMMP) research initiative for 1 to 2 years.

Product. A well coordinated CHAMMP Program.

Approach. The assignee will provide technical input to the Carbon Dioxide Research Program

staff, review program plans and proposals and make recommendations regarding their disposal, aid in coordinating project planning and research activities among CHAMMP investigators, and perform any other duties assigned that are consistent with detailee responsibilities and limitations established by DOE.

Results to Date. No results reported.

EXPLOITATION OF PARALLELISM IN CLIMATE MODELS

BAER, FERDINAND

UNIVERSITY OF MARYLAND

FY 1991	215
FY 1990	0
FY 1989	0

09/01/91-08/31/92

Objective. To explore new methods of general-circulation model (GCM) structure and execution that exploit massively parallel computer systems.

Product. Improved methods for describing physical processes in atmospheric and ocean GCMs, new algorithms to execute these models on massively parallel computer systems, and models for climate prediction studies.

Approach. New algorithms will be explored to allow the concurrent computation of several time levels in a GCM. These "time compression" algorithms will require that the models be restructured so that communication is minimized. Current GCMs require all grid points in the model to be marched forward concurrently, a step requiring communication and synchronization between the parallel processors.

Local subgrid-scale models will be developed that will provide the time- and space-averaged statistics to a climate model. These subgrid models will have a resolution that is independent of that of the climate model to encompass the appropriate range of spatial and temporal scales that are important to simulate the physical processes.

Massively parallel architectures will be used to concurrently execute multiple model simulations with different initial conditions to form an ensemble set of climate realizations.

STUDIES OF OCEAN PREDICTABILITY AT DECADE TO CENTURY TIME SCALES WITH A GLOBAL OCEAN GENERAL-CIRCULATION MODEL IN A PARALLEL-COMPUTING ENVIRONMENT

BARNETT, T. P., and MILLER, A.

SCRIPPS INSTITUTION OF OCEANOGRAPHY

FY 1991	16
FY 1990	0
FY 1989	0

09/01/91-08/31/92

Objective. To install a state-of-the-science ocean GCM on a massively parallel scientific computer and to carry out 100-year runs to explore the natural variability of the global ocean circulation.

Product. A quantification of the natural variability of the ocean component of the climate system.

Approach. The ocean GCM acquired from the Max Planck Institute (MPI) in Germany will be adapted to run on the Intel iPSC/860 parallel supercomputer at the San Diego Supercomputer Center (SDSC). This model has previously been run fully coupled to the MPI atmospheric GCM for a 100-year simulation. The code transfer to the SDSC parallel supercomputer will be carried out jointly between SDSC and Scripps personnel. Optimization and adjustments in the model's coding will be conducted through the

life of the project as experience on parallel computing platforms grows.

Two stochastic atmospheric-forcing models will be developed to form an interactive upper boundary for the ocean GCM. One model will be constructed from empirical orthoganal functions determined from global atmospheric data sets. "Noise" resulting from short-term weather events will then be filtered to isolate the longer-climate-scale driving modes. The data sets will then be reconstructed with a stochastic component added to the atmospheric model to reproduce the natural atmospheric variability resulting from the integration of the short-term events. A second model will be similarly constructed from atmospheric GCM-derived data.

The differences in equilibrium states produced in the ocean GCM by the two atmospheric models will be examined to determine the problems associated with coupling atmospheric and ocean GCMs, which currently tend to produce a climate that drifts away from the observed equilibrium state. The model will be run for 100-year simulations with each of the atmospheric forcing models.

Three 100-year model runs will be analyzed, the two mentioned above and a third in which the model is coupled to a full atmospheric GCM at MPI. Analysis and intercomparison of the three runs will determine the time and space scales of natural variability, the mechanisms of model climate drift, and preliminary estimates of the deterministic spatial and temporal limits of predictability of the ocean circulation.

CLIMATE SYSTEM MODELING PROGRAM

BRETHERTON, FRANCIS

UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

FY 1991	150
FY 1990	0
FY 1989	0

09/01/91-08/31/92

Objective. To undertake preliminary science and assessment activities leading to coordinated Earth-systems modeling and scientific assessment projects for the U.S Global Change Research Program.

Product. A plan for future Earth-systems modeling research and an assessment based on preliminary science investigations and a series of workshops.

Approach. A series of workshops on scientific and technical issues will be conducted to identify the key missing components in the U.S. climate and Earth-systems modeling activities. Preliminary studies in several of these areas will be undertaken by postdoctoral fellows working under the guidance of senior researchers.

CARBON DIOXIDE RESEARCH (CLIMATE MODELING)

CHEN, TSING-CHANG; GUSTAFSON, JOHN; and TAKLE, EUGENE

AMES LABORATORY

FY 1991	122
FY 1990	125
FY 1989	0

10/01/90-09/30/91

Objective. To adapt a well-developed global climate model and a fine-resolution mesoscale to execute on a massively parallel machine for regional climate research.

Product. A realization of the regional implications of global climate change.

Approach. Seasonal means for summer and winter will be computed for cyclone frequency, thunderstorm frequency, low-level circulation and low-level jet, water-vapor transport (divergent and rotational component), precipitation, and 500-mb height. These values will be analyzed with empirical-orthoganal-function analysis to establish the temporal and spatial relationships over the United States. The length of record for the elements varies from 5 decades to 12 years.

A similar analysis will be performed on mesoscale-model calculations. The NCAR GCM will be run for a 20-year simulation with fixed sea surface temperatures. A second, limited-area mesoscale model will be run with the daily fields from the NCAR GCM as the initial conditions. Both models will be adapted to run on massively parallel-processing machines. The result will be the restructured code for parallel processing and the demonstration of the technique of using a GCM as a driver for a mesoscale model.

Results to Date. No results reported.

SCIENTIFIC DEVELOPMENT OF A MASSIVELY PARALLEL OCEAN CLIMATE MODEL

CHERVIN, ROBERT M.

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

FY 1991	98
FY 1990	0
FY 1989	0

09/01/91-08/31/92

Objective. To develop the eddy-resolving Chervin-Semtner ocean general-circulation model (OGCM) to run on massively parallel scientific supercomputers.

Product. The development of state-of-the-science OGCMs on massively parallel computer architectures.

Approach. Heat transport by the ocean circulation, the effects of near-surface processes and their model parameterizations on long-term climate simulations, and model resolution requirements for climate modeling studies of the ocean circulation will be studied.

PARALLEL PROCESSING FOR ADVANCED PARALLEL CHEMISTRY (APACHE) CLIMATE MODELS

CLINE, RAYMOND E., JR.

SANDIA NATIONAL LABORATORIES

FY 1991	389
FY 1990	400
FY 1989	0

10/01/90-09/30/91

Objective. To develop parallel-processing techniques for the next-generation Advanced Circulation Model (ACM).

Product. Development of the radiation transport and atmospheric chemistry submodels of the ACM.

Approach. Software tools to permit the production of portable parallel code will be developed and used. Flexible software will be based upon a distributed-memory, distributed-instruction model. Programs developed for such a model can also be implemented on shared-memory multiprocessors.

At least two major coding revisions will be made as programming languages and tools evolve. The

near-term development will make use of existing portable systems and language extensions. The long-term development will exploit high-level object-oriented language approaches and descriptive languages that can produce machine-dependent code from a common source.

The Linda parallel language extensions will be considered for use as a near-term portable programming environment. The Linda system has been shown to be effective for programming shared-memory multiprocessors, network-distributed computing, and distributed-memory parallel processors. One of the initial goals of this work will be to compare programs developed with the Linda system with functionally identical code developed with the Oak Ridge PICL system, with the Argonne monitors and macros approach, and by Strand software systems.

Numeric methods will be developed to optimally exploit parallelism. Parallel implementations of these models would be greatly enhanced if the solution method required information that is local in space. The solution of chemical equations falls in this category, which may limit the applicability of spectral methods. Solving different model units (i.e., oceans and biosphere) with greatly different discretizations may also be necessary. The coupling of these model units may be accomplished more readily though the use of a finite-element formulation on the problem.

Experience suggests that the solution of flow fields can be efficiently performed on parallel machines. The treatment of radiation transport as a columnar process, as is done in current chemical models, may prohibit the use of adaptive-gridding techniques for the optimization of the solution of the finite-element equations. The same optimization benefits can be achieved for finite-element methods by using a fixed grid and adapting the order of the approximating polynomial. This technique is referred to as the adaptive p-method. The p-method can be viewed as a localized spectral method. The application of the adaptive finite-element p-method, as well as local mesh refinement for both the finite-difference and the finite-element methods, to climate modeling will be investigated.

Code structures that will permit the integration of climate submodels into the ACM will be developed. All of the relevant physical processes of a chemistry-radiation climate model will be represented by a common computational structure by imposing a 3-D mesh on the atmosphere. Chemical processes will then be solved internal to each mesh element, while radiation and flow calculations will require information exchange between elements. The radiation transport is currently treated as a 1-D problem with information passing down a column of mesh elements. The 3-D mesh imposed on the atmosphere contains a "short dimension," because we expect fewer mesh points to be in the altitude dimension than in the longitude or latitude. This situation permits the mesh to be mapped onto a 2-D array of computational elements. Because the chemistry and flow fields can be calculated with a 3-D array of processing elements, the choice for the best mapping of this problem onto a parallel platform will depend on the relative computational and communications performance of the two possibilities.

Results to Date. Algorithms for the resolution of the atmospheric dynamics have been identified and tested that have reduced the number of operations required to solve the problem by more than an order of magnitude. The Bi-CGSTAB method provided the largest reduction in the number of operations. The column-oriented radiation transport package has been parallelized, and the use of multiple processors per column has been shown to provide parallel speedups of a factor of ~70 versus a single processor and more than three times the performance of the current Cray version. We have also demonstrated a performance of more than 300 Mflops with less than 512 processors on the solution of the reaction/diffusion equations.

Our research in parallel algorithms and decomposition schemes has been extended to the application of ocean general-circulation models. A slab decomposition of the Semner-Chervin OGCM has been implemented on the nCUBE-2, and a decomposition method is currently being developed that will provide good load balancing for a finer decomposition of the irregular grid.

The use of parallel programming techniques that would provide portability across multiple platforms has also been investigated. Results with the Crystal compiler demonstrate the capability of obtaining good performance across both MIMD and SIMD platforms. Though this approach requires extensive recoding, it may prove to be a valuable alternative from the software-engineering viewpoint. The Linda language extensions have also been shown to provide portability with little cost compared to message-passing implementations. These results need to be extended to more-complex climate models to verify their utility in future model development.

STUDIES IN REGIONAL CLIMATE SENSITIVITY PREDICTABILITY AND TEMPORAL RESPONSE

CROWLEY, T. J., and NORTH, G. R.

APPLIED RESEARCH CORPORATION

FY 1991	143
FY 1990	0
FY 1989	0

09/01/91-08/31/92

Objective. To use noise-forced energy balance models (nf-EBMs) to study climate sensitivity to external forcing, regional climate response to increasing CO_2 concentration, the nonlinear effects of seasonal albedo changes, and differences in regional climate predictability resulting from geography.

Product. Preliminary estimates of climate sensitivities through multiple long-term integrations.

Approach. Climate sensitivity will be examined with parameters from the nf-EBM to see if climate sensitivity can be determined from correlation functions computed from available climate data sets. An understanding of the relationships between climate sensitivity and parameters in the nf-EBMs will be determined by comparing the correlations from the data with those from the model. The parameters in the model will be adjusted to give the correct correlations to yield quantitative information about the relationships among these parameters in the real climate system.

The hypothesis that the timing of the regional climatic response to increasing greenhouse gas concentrations may be dependent upon location will be tested.

A lag in the timing is expected to result from the differences in thermal capacity between the land and oceans. Transport by the atmospheric and ocean general circulations will not be included explicitly in the nf-EBM but will be accounted for by horizontal diffusion. The rate of diffusion will not be sufficiently fast to overcome the land-ocean differences in heat capacity, thereby producing geographically dependent lag in the timing of the climate system's response to greenhouse warming. Coupling the nf-EBM with an ocean upwelling-diffusion model will crudely simulate the ocean's role in delaying potential climate warming.

The linear and nonlinear effects of the nf-EBM runs will be separated by statistically comparing a version with an interactive snow albedo coupled to a seasonal cycle to a version without an interactive albedo.

Sophisticated statistical methods will be used to determine the capacity of several nf-EBMs to perform decade to century climate predictions.

CLIMATE-SYSTEM MODELING ON MASSIVELY PARALLEL COMPUTERS: I. GLOBAL OCEAN-CIRCULATION MODEL

DANNEVIK, WILLIAM P.

LAWRENCE LIVERMORE NATIONAL LABORATORY

FY 1991	146
FY 1990	150
FY 1989	0

10/01/90-09/30/91

Objective. To determine the degree to which advanced climate modeling efforts may benefit from current trends in the field of massively parallel supercomputing.

Product. The transfer of a highly vectorized ocean general-circulation model (GCM) running on a multiprocessor CRAY computer to a massively parallel computer (MPC) and its coupling to an atmospheric model.

Approach. An existing global, high-resolution, primitive-equation ocean-circulation model (OCM) will be ported onto the LLNL MPC. The selected model will be that of Semtner and Chervin, which is presently designed for vectorization on longitude and limited parallelization on latitude.

The sensitivity of alternative data-management strategies and physics-package algorithm selection in such a model will be evaluated with respect to issues of communication-latency tolerance; load balancing; and cache-, local-, and global-memory allocation on the MPC.

Model design elements will be optimized with regard to parallel scaling properties for the case in which the number of available processor elements becomes very large. Moreover, the developed strategies will be assessed for transfer to coupled atmosphere-ocean climate design efforts.

Results to Date. The global ocean-circulation model of Semtner and Chervin has been adapted to LLNL's BBN TC2000 parallel system, which is capable of supporting both shared- and distributed-memory programming models. One version of the parallel model uses a 1-D domain decomposition and split-join shared-memory paradigm, which is similar to that employed by Semtner and Chervin for the CRAY multiprocessor environment. Parallel efficiency has been good for processor counts in the range from 2 to 10 with this approach. For larger processor counts, load imbalance and network contention factors lead to degraded parallel performance.

A programming paradigm based on a (horizontal) 2-D-domain-decomposition, distributed-memory/message-passing approach has also been developed. Here, parallel efficiency is determined by the ratio of communication-to-computation, which scales as the ratio of area to volume for the subdomains. We have found parallel efficiency in excess of 90% for processor counts in the range 2 to 128 for this paradigm for a $1/2^{o}$ x $1/2^{o}$ resolution test case, and developed a performance model for this approach that allows prediction of parallel throughput as a function of processor count, spatial resolution, and finite-difference-algorithm selection. The success with this paradigm has led to a design for a parallel, coupled, ocean-atmosphere general-circulation model that will be portable within the MIMD machine class.

THE LAND COMPONENT OF THE GLOBAL CLIMATE SYSTEM WITH ADEQUATE SPATIAL RESOLUTION

DICKINSON, ROBERT E.

UNIVERSITY OF ARIZONA

FY 1991	117
FY 1990	0
FY 1989	0

09/01/91-08/31/92

Objective. To develop land-surface-process parameterizations for general-circulation models (GCMs).

Product. An improved land-surface description for use in current climate models.

Approach. The current BATS code will be recoded, restructured, and documented to make it conform to programming standards now adopted by the climate modeling community. Subsequent experiments will be performed with the scheme to identify its shortcomings and weaknesses for the next stage of development. A version of this code will be developed to conduct simulations at 0.5^{o} land-surface resolution independent of GCM grid resolution. A subgrid-scale description will be developed from GCM grid-scale average precipitation, radiation, and cloudiness for use by the BATS parameterization. Sensitivity experiments will be conducted with BATS implemented within the National Center for Atmospheric Research's Community Climate Model (Version 2), a state-of-the-science spectral-transform climate model, to test the scheme's ability to simulate climate anomalies. And simple visualization tools will be developed to enhance evaluation of fine-mesh output.

DEVELOPMENT OF AN ADVANCED REPRESENTATION OF CUMULUS CONVECTION

EMANUEL, KERRY A.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

FY 1991	85
FY 1990	0
FY 1989	0

09/01/91-08/31/92

Objective. To develop a new model of cumulus transport within a general-circulation model (GCM) that uses a different hypothesis from the entraining-cloud model now in widespread use.

Product. The development of cumulus-convection parameterizations for atmospheric GCMs.

Approach. The simulation of climate with GCMs requires the accurate description of cloud effects. Cumulus clouds are active in the vertical mixing of atmospheric water, heat, and momentum. Recent observations will be used to develop a new model of cumulus transport within a GCM that uses an episodic mixing approach, in which parcels enter the cloud at cloud base, move vertically through the cloud in updrafts without mixing, then instantaneously mix with their environment upon reaching the neutral-buoyancy level. Cloud microphysical parameters will determine the amount of cloud water converted to precipitation.

PARALLEL ATMOSPHERIC CLIMATE MODEL

FOSTER, I. T.

ARGONNE NATIONAL LABORATORY

FY 1991	195
FY 1990	200
FY 1989	0

10/01/90-09/30/91

Objective. To provide the technological advances in numeric methods and parallel processing required to support the modeling of the atmospheric component of the climate system on advanced-computing architectures (i.e., massively parallel computers).

Product. An advanced climate model with significantly greater capability than that of current models.

Approach. Interdisciplinary teams will be established at Argonne National Laboratory,

Oak Ridge National Laboratory, and the National Center for Atmospheric Research (NCAR) to conduct research in advanced numeric methods, model development, and parallel software tools.

Both parallel algorithms for existing numeric methods and new methods and algorithms suitable for large-scale parallel climate models will be developed and evaluated. Prototype implementations of methods and algorithms applied to the shallow-water equations on the sphere will be used to study accuracy, efficiency, and suitability for massively parallel execution.

An existing climate model (NCAR Community Climate Model, CCM2) will be investigated with the intention of developing a usable parallel implementation for distributed-memory MIMD computers. Algorithms and methods developed earlier as well as techniques for including new model physics will be incorporated into the parallelized CCM2 for further evaluation.

Parallel software techniques and tools will be designed and developed to support algorithm development. These tools will be intended to support the archiving of expertise developed in the project and the performance evaluation and characterization of large-scale parallel codes.

Results to Date. A preliminary parallel implementation of CCM2 was constructed in collaboration with Oak Ridge National Laboratory. This work built on algorithms, libraries, and implementation techniques prototyped during FY90. The parallel code was demonstrated on the 528-node Intel Touchstone DELTA computer. Validation, performance studies, and tuning are continuing.

Analytic studies of the parallel scalability of the spectral-transform method used in CCM2 were conducted. Simple analytic models were calibrated with empirical performance data and then used to explore performance issues, providing important input for the design of future parallel models.

CCM2 routines dealing with gravity waves and radiation are not invoked at all grid points. An instrumented CCM2 was used to quantify the effect of the resulting load imbalance on parallel efficiency. A performance degradation of about 20% was observed. Load-balancing strategies are now being investigated.

A control-volume method based on an icosahedral-hexagonal grid was designed and implemented for the shallow-water equations. Studies showed that the method overcomes problems encountered by previous investigators. A parallel implementation was constructed and used for performance studies. This code was the first application to run on the DELTA.

STUDIES OF OCEAN PREDICTABILITY AT DECADE TO CENTURY TIME SCALES WITH A GLOBAL OCEAN GENERAL-CIRCULATION MODEL IN A PARALLEL-COMPUTING ENVIRONMENT

LEARY, ROBERT H.

GENERAL ATOMICS, SAN DIEGO SUPERCOMPUTER CENTER

FY 1991	81
FY 1990	0
FY 1989	0

09/01/91-08/31/92

Objective. To install a state-of-the-science ocean general-circulation model (GCM) on a massively parallel scientific computer and to carry out 100-year runs to explore the natural variability of the global ocean circulation.

Product. A quantification of the natural variability of the ocean component of the climate system, experience in using massively parallel computers to run GCMs, and an understanding of the problems associated with coupling a full atmospheric GCM with an ocean GCM.

Approach. The ocean GCM acquired from the Max Planck Institute (MPI) in Germany will be adapted to run on the Intel iPSC/860 parallel supercomputer at the San Diego Supercomputer Center (SDSC). This model has previously been run fully coupled to the MPI atmospheric GCM for a 100-year simulation. The code transfer to the SDSC parallel supercomputer will be carried out jointly by personnel from the SDSC and Scripps Institution of Oceanography. Optimization and adjustments in the model's coding will be conducted through the life of the project as experience on parallel computing platforms grows.

Two stochastic atmospheric-forcing models will be developed to form an interactive upper boundary for the ocean GCM. One model will be constructed from empirical orthoganal functions determined from global atmospheric data sets. "Noise" resulting from short-term weather events will then be filtered to isolate the longer-climate-scale driving modes. The data sets will then be reconstructed with a stochastic component added to the atmospheric model to reproduce the natural atmospheric variability resulting from the integration of the short-term events. A second model will be similarly constructed from atmospheric GCM-derived data.

The differences in equilibrium states produced in the ocean GCM by the two atmospheric models will be examined to determine the problems associated with coupling atmospheric and ocean GCMs, which currently tend to produce a climate that drifts away from the observed equilibrium state. The model will be run for 100-year simulations with each of the atmospheric forcing models.

Three 100-year model runs will be analyzed, the two mentioned above and a third in which the model is coupled to a full atmospheric GCM at MPI. Analysis and intercomparison of the three runs will determine the time and space scales of natural variability, the mechanisms of model climate drift, and preliminary estimates of the deterministic spatial and temporal limits of predictability of the ocean circulation.

CHAMMP INITIATIVE ORGANIZATION

MacCRACKEN, MICHAEL C.

LAWRENCE LIVERMORE NATIONAL LABORATORY

FY 1991	225
FY 1990	180
FY 1989	0

10/01/90-09/30/91

Objective. To provide leadership for the initial stages of the CHAMMP program, developing a program to meet the goal of producing a new generation of climate models able to provide convincing estimates of the potential time-dependent, regional changes in climate that may result from the increasing atmospheric concentrations of CO_2 and other greenhouse gases.

Product. A program-design report presenting the intent and implementation plan for the CHAMMP program that is suitable for review by the scientific community and coordination with other agency initiatives; organization of the CHAMMP Science Team and of scientific workshops and meetings.

Approach. The community of researchers will be brought together and involved in prototype studies that will allow both the study of the challenges to be faced and the production of versions of existing models that perform well in a massively parallel environment. Design criteria for the next generation of models will be developed.

Initial versions of advanced models will be constructed and tested on machines capable of increasing throughput by a factor of 10^2 to 10^3. This effort will require close coordination of the efforts of many groups.

The initial versions of the advanced models will be extended in their physics, transferred to even-faster machines, is further optimized in performance, and used in model simulations.

Results to Date. The CHAMMP program plan was issued in November 1990 after scientific and agency reviews. Based on the plan, a request for proposals was drafted by DOE, and proposals were solicited and reviewed. The Science Team is in the process of formation. Discussions are underway with the CSMP on a coordinated workshop. A review of the program status was conducted by JASON. A keynote speaker and minisymposium on the general topic of computing and global modeling have been arranged for Supercomputing '91. Topics and speakers are being recommended for a NATO research workshop on supercomputing and climate modeling.

MANAGEMENT OF THE MODEL-DEVELOPMENT COMPONENT OF THE CHAMMP PROGRAM

MALONE, ROBERT C.

LOS ALAMOS NATIONAL LABORATORY

FY 1991	150
FY 1990	0
FY 1989	0

12/01/90-09/30/91

Objective. To provide technical leadership for the model-development component of the DOE CHAMMP global modeling program.

Product. A research plan for the model-development component of the CHAMMP initiative.

Approach. We will work with DOE management to define the scope, objective, and timetable for CHAMMP; help define tasks to be pursued under the auspices of CHAMMP; and identify well qualified personnel within DOE laboratories, universities, and other institutions to carry out those tasks. A well integrated model-development program will be fashioned that complements the activities carried out under the proposal-driven Science Projects component and establishes a technical framework that can incorporate advances made within the DOE High Performance Computing initiative and the global climate modeling programs of other federal agencies.

Results to Date. A research plan has been formulated for the initial phase of the model-development component of the CHAMMP Program. Strong emphasis will be placed on the efficient implementation on massively parallel computers of several atmospheric and oceanic general-circulation models (GCMs). GCMs that employ different numeric methods and alternative representations of physical processes will be investigated to better understand their relative merits for massively parallel computers. Because computer technology and programming techniques are still evolving rapidly (particularly with regard to massively parallel computers), a balanced approach has been adopted to investigate both SIMD and MIMD computers, and both data-parallel (e.g., Fortran-90 array constructs) and control-parallel language representations. The model-development plan has been fashioned to complement and integrate activities funded under the science-projects component of CHAMMP.

CRAY COMPUTER

McCURDY, WILLIAM

LAWRENCE LIVERMORE NATIONAL LABORATORY

FY 1991	2800
FY 1990	3100
FY 1989	0

10/01/90-09/30/91

Objective. To Provide the climate-modeling community with a substantial amount of computing resources (14,000 CRAY-1 equivalent hours) to conduct long climate model simulations.

Product. Long-model-run results for global-change studies and identification of model properties and characteristics in long-term simulations.

Approach. Computing resources on the CRAY-1 at Lawrence Livermore National Laboratory will be made available to global-climate-change researchers.

Results to Date. Large blocks of time were granted to climate researchers to perform long climate model simulations of decade to century scale. Approximately half of the resources were dedicated to participants in the World Climate Research Program's Atmospheric Model Intercomparison Project.

LOOSELY COUPLED DISTRIBUTED MODELING OF CLIMATE CHANGE

PEIERLS, R. F., and MICHAEL, P. A.

BROOKHAVEN NATIONAL LABORATORY

FY 1991	195
FY 1990	200
FY 1989	0

10/01/90-09/30/91

Objective. To develop methods of running coupled submodels of Advanced Climate Models (ACMs) simultaneously on separate processors.

Product. Techniques that allow the power of physically separated computers to be harnessed for a single model computation, which should alleviate some of the serious software problems inherent in building large, complex climate models.

Approach. The modeling of the climate system will be decomposed to treat different processes coupled only loosely in time. In such a situation, the exchange of information between processes need not be strictly constrained in phase. Such asynchronous coupling will allow exploration of alternative computing approaches.

Three computing environments will be explored: shared-memory multiprocessor systems (e.g., IBM 3090/x00 and Cray X/MP); heterogeneous computers linked by a local area network; and geographically separate, network-connected supercomputers.

Tests will be performed with two kinds of prototype models. Highly parameterized models of the atmosphere, ocean, sea ice, chemical constituents, ecosystems, etc. will be run in a coupled mode to test constraints resulting from the intrinsic time structure of the various subsystems and the interaction of multiple subsystems. Detailed regional atmospheric and ocean-basin models will define data-transfer requirements. Final testing will use full-scale atmospheric- and oceanic-circulation models.

The evaluation will compare traditional climate variables, such as the seasonal and latitudinal dependence of temperature, as well as various fluxes to expose differences in any compensating errors.

Results to Date. A very highly parameterized prototype climate model containing four coupled components (an energy balance atmosphere model, an upwelling diffusion 1-D ocean model, a parameterized response model describing anthropogenic emissions dependent on global temperature, and a parameterized model of CO_2 absorption by the ocean and infrared emission) was first run as a serial computation, with each module invoked at a regular time step. It was then run as a loosely coupled parallel computation, first in multitasking mode on a CRAY-2 and then with each module independently executing on a node on a heterogeneous local area network. The

dependence of the results on the allowed time lag between the modeled times of the four modules was studied. The results strongly suggest that major features of the climate behavior should not be sensitive to time lags of the order of a few time steps. Some preliminary tests of the procedures required to couple independently composed submodels were also carried out with the SPEM ocean model of Haidvogel et al. coupled to a prescribed atmospheric wind field calculated as an explicit function of time.

DEVELOPMENT OF AN ADVANCED FINITE-DIFFERENCE ATMOSPHERIC GENERAL-CIRCULATION MODEL

RANDALL, DAVID A.

COLORADO STATE UNIVERSITY

FY 1991	83
FY 1990	0
FY 1989	0

09/01/91-08/31/92

Objective. To develop a higher-resolution finite-difference model with improved process parameterizations that is suitable for a massively parallel computing environment.

Product. Improved methods for describing physical processes in atmospheric and ocean general-circulation models (GCMs) and the development of these models on massively parallel computer systems to carry out climate-prediction studies.

Approach. A documented copy of the current model code will be made available to the CHAMMP science team investigators on a parallel supercomputer. As improvements to the model are made at CSU and UCLA, they will be transferred to the CHAMMP community. Improved physical parameterizations will be developed for cloud processes, convection, land surface exchange, and the planetary boundary layer based on information from recent observational programs and theoretical advances.

The computational framework of the model will be improved. Recent developments in more accurate numerical methods will be incorporated into the model so that it more faithfully simulates the real atmosphere, particularly in its representation of flow near the poles. These improved formulations will partially overcome the inaccuracies in finite-difference modeling that gave rise to the spectral models.

Sensitivity experiments will be run to test the improved parameterizations and methods as a function of model resolution. Models perform better at higher resolution because the process parameterizations are more faithful to the real world at finer spatial scales. These sensitivity tests will examine how well the parameterizations scale with different grid spacings.

SYMMETRIC TRUNCATION OF THE SHALLOW-WATER EQUATIONS

ROUHI, SAFIALI

UNIVERSITY OF CALIFORNIA AT SAN DIEGO

FY 1991	105
FY 1990	0
FY 1989	0

09/01/91-08/31/92

Objective. To develop a novel numeric framework to model geophysical fluid dynamics that may be superior to currently used methods.

Product. Alternative numeric methods for general-circulation models (GCMs) of the atmosphere and ocean that can be executed on massively parallel computer systems.

Approach. The inviscid Lagrangian formulation of the shallow-water equations may belong to a Hamiltonian or friction-free system in which,

theoretically, infinitely many conservation properties exist, many of which may be relevant to the global geophysical-flow problem. Symmetric truncation will be used to develop a model system in which the number of conserved properties will increase as the degrees of freedom in the model increase. This system will be used to explore the relationship between conserved properties and accuracy of the model. Reduction will then be used to cast the model in an Eulerian framework that will ultimately be required in a full climate model.

SCIENTIFIC DEVELOPMENT OF A MASSIVELY PARALLEL OCEAN CLIMATE MODEL

SEMTNER, ALBERT J.

NAVAL POSTGRADUATE SCHOOL

FY 1991	87
FY 1990	0
FY 1989	0

09/01/91-08/31/92

Objective. To develop the eddy-resolving Chervin-Semtner ocean general-circulation model (OGCM) to run on massively parallel scientific supercomputers.

Product. The development of state-of-the-science OGCMs on massively parallel computer architectures.

Approach. Heat transport by the ocean circulation, the effects of near-surface processes and their model parameterizations on long-term climate simulations, and model resolution requirements for climate modeling studies of the ocean circulation will be studied.

MASSIVELY PARALLEL ADAPTIVE ACM

TREASE, HAROLD

LOS ALAMOS NATIONAL LABORATORY

FY 1991	350
FY 1990	360
FY 1989	0

10/01/90-09/30/91

Objective. To improve the current state-of-the-art in global climate modeling through the creative use of massively parallel computing hardware and algorithms along with improvement in the underlying numeric models.

Product. A new basis for the atmospheric-dynamics component of the Advanced Climate Model (ACM) of the CHAMMP Program.

Approach. The current LANL 3-D code will provide a framework for the new ACM, allowing us to rapidly prototype new model-physics algorithms within the context of an existing code and freeing us from having to worry about programming details, such as data management, I/O, and the user interface.

An adaptive-mesh technique called the free-Lagrange method will be used as the basis for the new GCM. This method gives the freedom to dynamically add (or remove) mesh resolution to capture such flow features as fronts, vortices, and shear layers. The Lagrangian nature of our current implementation will be modified to account for the boundary-layer behavior of the atmosphere relative to global circulation patterns.

Current massively parallel hardware will be used as a platform upon which to build the parallel algorithms.

Each piece of model physics will be implemented in such a manner that the algorithms take

advantage of the parallel nature of the machines on which they are run.

Results to Date. No results reported.

PARALLEL ATMOSPHERIC CLIMATE MODEL

WARD, ROBERT C.

OAK RIDGE NATIONAL LABORATORY

FY 1991	778
FY 1990	800
FY 1989	0

10/01/90-09/30/91

Objective. To provide a usable parallel implementation of an existing model for use by modelers, to investigate the coupling of the parallel atmospheric model with other components of a climate-simulation system, to produce algorithm libraries and software tools to aid in the development of parallel climate models, and to sponsor workshops for sharing information among the climate-modeling community.

Product. The advances in numeric methods and parallel-processing techniques required to support the modeling of the atmospheric component of the climate system on advanced computing architectures (i.e., massively parallel computers).

Approach. Work will begin on parallel implementations of three existing methods in prototypes for MIMD and SIMD machines. Both SIMD and MIMD parallel computers will be examined in this project to maintain generality for the coupling of the atmospheric model with other components of the global climate system. The aim of this work will be to evaluate the suitability of these methods for large-scale parallel execution. The prototypes will apply the spectral method, finite-difference method, and a composite-mesh finite-difference method to the nonlinear shallow-water equations on the sphere.

A portable parallel version of the NCAR Community Climate Model, CCM2, will be developed. This code will be designed to run on distributed-memory MIMD computers, such as Intel iPSC/860, BBN Butterfly, and NCube machines. Only the Intel computer will be our initial computational engine. The initial work will be to modify the existing CCM2 to run on medium-grained parallel processors, to isolate sequential bottlenecks and other deficiencies in the existing algorithms, and to quantify load imbalances caused by model physics.

The development of a portable version of the Cray code will be completed with profiling tools to identify computationally intensive components; a workshop will be held to discuss approaches to parallelization and to devise an initial strategy; then the recommendations of the workshop will be implemented in an incremental fashion with both FORTRAN and higher-level languages. Both versions will use PICL and other software tools for portability and performance evaluation and characterization.

To be able to address the computational problems associated with advanced model physics, the existing CCM2 will be extended by coupling it with a vegetation model. The computational load of the coupled system will be measured.

The biosphere-atmosphere coupling will use the existing BATS interface to CCM2. The description of the interaction between the atmospheric and terrestrial systems will be restricted to exchange fluxes.

Activity in performance-monitoring tools will focus on improvement to data-reduction and data-collection techniques and on improved graphic tools for presenting decompositions and performance data. Existing tools will be extended and validated for data reduction and collection on a parallel computer with about 100 nodes.

Existing graphic tools will be extended for visualizing the decompositions employed in the initial parallel version of CCM2 and the parallel-algorithm prototypes.

A workshop will be held at Argonne National Laboratory on "Parallel Programming: Tools and Concepts for Advanced Climate Models." Two further topics for workshops are numeric methods and model physics.

Results to Date. The collaborative relationship between researchers at NCAR, ORNL, and Argonne has continued in FY91 and been productive in a number of areas. From broad definition of the issues in using massively parallel computers for climate modeling, the group has moved to providing solutions to some of the more difficult specific problems of the parallel computation of atmospheric dynamics.

The primary goal of our work is to make CCM2 available on parallel computers. The CCM2 code is currently in the prerelease phase at NCAR on the CRAY Y-MP. Parallel implementations on both MIMD and SIMD computers are well under way, though use for climate studies awaits certification by NCAR of both the sequential and the parallel versions.

A parallel spectral-transform algorithm for MIMD computers based on a lon-lat decomposition has been developed and applied to the parallel solution of the shallow-water equations on the sphere. The shallow-water equations on the sphere have been solved with a parallel FFT and parallel Legendre transform developed for the CM2. A parallel implementation of the prerelease Community Climate Model (CCM2) with latitude decomposition has been developed for the Intel iPSC/860. A standard set of test problems designed to evaluate numeric methods for atmospheric flow has been defined; these test cases include a performance benchmark for parallel computation. The benchmarking of the spectral transform method on the problems of the test set is nearly complete. Efficient parallel FFT algorithms, tailored for the solution of the atmospheric flow problems, have been implemented on both the CM2 and the Intel iPSC/860.

The development and study of parallel algorithms for the spectral transform method on both MIMD and SIMD computers has progressed to the point that these are being applied to preliminary parallel implementations of the CCM2. A lon-lat decomposition of CCM2 is currently under way in joint work with our collaborators at Argonne. This will become PCCM2 Version 1.0 after testing and verification with the NCAR Cray version.

SCIENTIFIC DEVELOPMENT OF THE ADVANCED PARALLEL CHEMISTRY (APACHE) CLIMATE MODEL

WUEBBLES, DONALD J.

LAWRENCE LIVERMORE NATIONAL LABORATORY

FY 1991	282
FY 1990	290
FY 1989	0

10/01/90-09/30/91

Objective. To lead the development of detailed simulation components of the chemical, radiative, and transport processes occuring in the global atmosphere during the development of the Advanced Climate Model (ACM) under the CHAMMP Program.

Product. A highly advanced capability for the investigation of energy and environmental issues.

Approach. The optimal treatment of the chemical and physical processes to be included in the model to ensure a high quality, but computationally efficient, product will be determined. The scientific components of the chemical, radiative, and transport submodels will be designed and developed. The necessary

studies to evaluate and validate the resulting submodels will be performed.

Results to Date. The LLNL 2-D radiative-chemical-transport code has been ported to a massively parallel machine and split into smaller portions, which were individually parallelized. Large increases in computational speed were found for the radiation and chemistry solvers. Optimal numeric methods were investigated for a newly reformulated dynamics portion of the code that resulted in a decrease in the number of iterations needed for accurate solutions to one-thirtieth what was needed before. A survey of numeric techniques for advective transport in the next-generation chemical-transport code was done. This study centered on accurate methods that also lent themselves to massively parallel computers, which led to an initial conclusion that the best overall base for development of a 3-D chemical-transport model is likely to be an Eulerian mesh with adaptive mesh refinement. In preparation for future 3-D studies, an existing 3-D tracer-transport model was obtained. This model provides a head start in our model development by forming a building block for the development of the next-generation chemical-transport model.

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 plant 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 vegetation effects 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 to plant physiology and to system-level properties, such as productivity, yield, structure, function, and plant-animal-microbial relationships. Effects of CO_2 and climate change on plant and system-level hydrological conditions will also be considered.

Primary products will be experimental data and process models of plant response to variable CO_2 and climate conditions. As a general requirement, the research products represent plant and system-level effects of CO_2 and climate change.

Research Objectives. The first objective is to improve our capability of predicting effects with vegetation from more CO_2 and different climate conditions. The second is to search for existing evidence of biological response to atmospheric CO_2 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. And the third is to determine experimentally the role of plants in fixing atmospheric CO_2 as a sink mechanism in the global carbon balance.

Research Questions. Examples of questions to be addressed are:

- How much does plant growth, productivity, and carbon content change in relation to more CO_2 and associated climate changes? At the fundamental system level, what are the interactive effects of simultaneous changes of these and other variables on photosynthesis and transpiration?
- How will the functional and structural properties of plants and ecosystems change with different CO_2 and climate regimes?
- What historical or paleo records would be useful for detection of changes of plant and ecosystem response to variable CO_2 and climate?

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Research Summaries

SIMULATION MODELING OF CROP RESPONSE TO CO_2 ENRICHMENT

ACOCK, BASIL

SYSTEMS RESEARCH LABORATORY

FY 1991	60
FY 1990	100
FY 1989	100

09/01/91-08/31/92

Objective. To define a "generic" modular structure for models of plant growth and to develop and test modules needed as components of modular crop models; to perform sensitivity/uncertainty analysis of GLYCIM; and to exercise the models in studies of the combined effects of CO_2 and temperature on plant growth.

Product. A validated, mechanistically based plant-growth simulation model that can treat CO_2-dependent physiological processes 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, and ways will be explored 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 treat 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 United States.

Sensitivity/uncertainty analysis of the soybean GLYCIM model will continue. Because this model is the most thoroughly tested of all physiologically based plant models, aggregate predictions will attempt to account for production over wide areas. The models will attempt to link to the lower boundary of the general-circulation models, with initial attention to partitioning of energy at the surface. Albedo and stomatal conductance will be the initial processes examined.

Refinement of plant-model controls on carbon fixation and utilization in growth will be completed for COTCO2, a state-of-the-art plant-growth model developed jointly by DOE and the USDA/ARS. Data from other CO_2-temperature experiments with wheat will be adapted to existing wheat models, and a new model will be developed for rice.

Results to Date. Documentation for the modular version of GLYCIM, the soybean crop simulator, was completed and published during the year.

SOILSIM, a 2-D model of soil processes was interfaced to GLYCIM. Uncertainty analysis of the GLYCIM/SOILSIM combination, using PRISM on the CRAY, commenced. Subroutines were added to SOILSIM to deal with the movement of multiple solutes in the soil and to add soil-temperature prediction.

A major defect of all existing soybean models is their inability to accurately predict the time of flowering under all conditions. Further experiments on the control of flowering in soybean by temperature and day length were performed in controlled-environment plant-growth cabinets. Plants in these experiments failed to show the response to direction of change in day length that has been observed in

naturally varying day lengths. The flowering response of soybeans remains a mystery for the present.

Attempts to estimate solar radiation in the absence of direct observations were unsuccessful. Cloud cover is routinely collected at many sites, such as airports, but the necessary data on visibility are either unavailable or of dubious value.

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 1991	150
FY 1990	260
FY 1989	250

09/01/91-08/31/92

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; and 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; a simulation model of 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 different climate regimes.

Approach. The Plant Stress and Protection Research Unit is conducting a long-term 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. The experiments will derive response functions to CO_2 concentration under conditions of nonlimiting 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.

The combined temperature-CO_2 effects will be examined for several new cultivars obtained from the International Rice Research Institute. Ancillary measurements of CH_4 emissions in relation to varied environmental conditions (temperature and nutrient status) and physiological status will identify biophysical controls on its release from paddy rice. Companion experiments will investigate interactive effects of CO_2 and nitrogen fertilization. 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 June to September, 1990. In all six chambers, the day/night air temperatures were maintained at 29/21°C while the paddy water temperature was controlled to a constant 25°C. Three chambers were maintained at a CO_2 concentration of 330 ppm, and the remaining three chambers at 660 ppm. Within each CO_2 treatment, a high, medium, and low amount of urea nitrogen fertilizer was applied: 200, 100, or 0 kg N ha^{-1}. The urea was applied in three split applications during the growing season.

Both increasing nitrogen fertilization and CO_2 enrichment resulted in increasing tillering and greater final above-ground biomass.

Photosynthesis was increased by both CO_2 enrichment and increasing nitrogen treatment. Evapotranspiration was decreased by CO_2 enrichment and increased with increasing nitrogen treatment.

Grain yield was significantly increased with both CO_2 enrichment and increased nitrogen fertility. With increasing nitrogen application rates (from 0 to 200 kg N ha^{-1}), grain yield increased from 6.0 to 8.1 and 7.9 to 10.1 metric tons per hectare for the 330- and 660-ppm CO_2 treatments, respectively. This increased grain yield was a result of the production of more panicles per plant with CO_2 enrichment and with increasing nitrogen treatment.

These results indicate that global increases in CO_2 should be beneficial for rice production. However, the results of this experiment suggest that, in order to take full advantage of CO_2 enrichment, more nitrogen fertilizer may be required.

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

BAZZAZ, F.A.

HARVARD UNIVERSITY

FY 1991	240
FY 1990	183
FY 1989	229

04/15/91-03/31/92

Objective. To obtain data for predicting the effects of CO_2 and of other physical influences (e.g., light and moisture) on plant communities based on knowledge of component species and their growth, productivity response, and resource use.

Product. Data on growth and physiology of individuals and mixtures of species will be produced at several levels of CO_2. Responses of individuals and mixtures will be parameterized, and data will be used in models describing CO_2 effect on plant competition in relation to CO_2 and other environmental variables.

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).

Specific data for modeling community response to CO_2, temperature, and light will also be obtained. 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 CO_2 and light conditions associated with photosynthesis.

Results to Date. Our laboratory has focused on understanding the physiological and growth responses of deciduous tree seedlings to elevated atmospheric CO_2. With this information we hope to establish a predictive model of the impact of elevated CO_2 on temperate forest ecosystems.

Elevated atmospheric CO_2 enhances the growth of most species, and species differ greatly in responsiveness to elevated CO_2. CO_2 growth enhancement is influence more by nutrient availability for early-successional species and by

light availability for late-successional species. Elevated CO_2 increases the growth of red maple (but not of gray birch) in flooded soils. Conversely, the growth of gray birch (but not of red maple) is increased in extremely dry soils. These results suggest that competition between these species may be minimized through increased niche differentiation in an elevated-CO_2 world.

We have found that pot shape and volume influence how plants respond to elevated CO_2. Increases in mean density of roots produced and the spatial variation in the distribution of roots at elevated CO_2 are altered with pot volume and shape. Root restriction, either by limiting rooting volume or by altering the dimensions of the rooting space, reduces CO_2 enhancement of whole-plant growth and reproductive output disproportionately more than leaf-level photosynthesis.

EFFECTS OF ENRICHED CO_2, WATER, AND NUTRIENT STRESS ON SWEET POTATOES: TOWARDS THE DEVELOPMENT OF A UNIVERSAL CROP SIMULATION MODEL

BISWAS, P. K.

TUSKEGEE INSTITUTE

FY 1991	180
FY 1990	170
FY 1989	150

09/15/91-09/14/92

Objective. To determine the interaction of water stress with CO_2 enrichment on field-grown sweet potatoes, including growth, yield, physiology, rhizosphere biochemistry, and soil microbial activity; to determine the interaction of nutrients (nitrogen, phosphorous, and potassium) with CO_2 enrichment, looking at the same endpoints; and to determine the interaction of potassium only with CO_2 enrichment, looking at the same endpoints.

Product. New data on the physiology and growth of sweet potatoes and on the interactive effects of CO_2, water, and nutrient stress.

Approach. Field experiments will be carried out with open-topped chambers that have been well calibrated for this type of research. The experimental design will examine physiology and growth differences as a function of different CO_2 concentrations. The experiments will produce data on the physiological, photosynthetic, and biochemical characteristics of sweet potato in relation to variations in CO_2 concentration in combination with different water and nutrient treatments. The growth, morphological, physiological, and rhizosphere biochemistry responses will be examined at the different treatments. The research will focus on an apparent potassium deficiency that is often observed when plants are grown at elevated CO_2.

Results to Date. Our 1991 field experiment was designed to study the interactive effects of CO_2 and water supply on sweet potatoes. Sweet potatoes were grown in open-topped chambers. Rain shelters and soil-moisture barriers were added to the open-topped chambers in order to exclude rainfall. Each chamber was equipped with its own separate irrigation system and water meter.

The experimental design consisted of three CO_2 treatments (open-field plot, chamber with no CO_2 added, chamber with 300 μL/L of CO_2 added), two water treatments, and four replicates. "Wet" plots were irrigated every 5 days at a rate equal to the long-term average precipitation for the area. "Dry" plots were irrigated every 10 days at a rate equal to 50% of the long-term average precipitation. Soil moisture was monitored in each chamber with a neutron probe. During each irrigation cycle, measurements were made of photosynthesis, stomatal conductance, and water potential. In addition, periodic measurements were made of shoot growth, leaf temperatures, night leaf respiration, and soil nutrients and soil microbial activity.

PHOTOSYNTHETIC ACCLIMATION TO ELEVATED CO_2: BASIS FOR VARIABILITY AMONG PLANTS

CURE, JENNIFER D.

DUKE UNIVERSITY

FY 1991	50
FY 1990	146
FY 1989	139

09/01/91-08/31/92

Objective. (1) To examine the rate or extent of acclimation of P_s (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. (2) To describe biochemically the time course of acclimation 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. And (3) to survey leaf tissues, significant changes in leaf structure, and changes in cell properties among the various photosynthetic tissues of the leaf.

Product. Experimental data on the effects of CO_2 enrichment on the causes of and variability in P_s acclimation response to CO_2; data on the time course of changes in gas-exchange patterns simultaneous with changes in carbon allocation and RuBisCo activity; and evaluations of the proportional contribution of leaf morphological adaptations to the overall acclimation process.

Approach. Experiments will be completed and results will be published.

Results to Date. Initial studies of photosynthetic acclimation of kudzu in different light regimes were hampered by problems with the gas-exchange system used. Our first objective for the year, therefore, was to construct and test an accurate rapid-response gas-exchange system with which to study regulation of the Calvin cycle and photosynthetic adjustment of plants acclimating to elevated CO_2. The gas-exchange system was completed and tested and is functioning well. Its key features are the small volume of the leaf cuvette and the instantaneous switching from one given gas composition to a second. Measurement of gas exchange is sufficiently rapid to bypass slow stomatal responses and changes in activation state of RuBisCo, thus greatly facilitating the measurement of carboxylation efficiency (C.E.). This open system also can be used to measure postillumination CO_2 uptake (assimilatory charge, A.C.) and O_2-, light-, and high-CO_2-induced photosynthetic oscillations.

Using this system, we studied the high-CO_2 acclimation of the sunflower. The focus of the study was leaf tissue developed at ambient CO_2 and transferred to 700 μL/L CO_2 for about 2 weeks. C.E. (which describes RuBisCo activity) declined for all treatments with time, but declined more rapidly for high-CO_2 leaves than for controls. High-CO_2 plants tended to show a lower A.C. in both nitrogen treatments. C.E. per unit A.C. remained stable for plants at 350 μL/L but declined for high-CO_2 plants throughout the 2-week acclimation period. Nitrogen treatment had no effect on these patterns.

In a second study, a tobacco mutant lacking phosphoglucomutase was used for studying the role of starch synthesis in regulation of the Calvin cycle. Results showed that the mutant and wild type differed not at all in C.E., the initial slope of the photosynthetic CO_2 response curve, or in photosynthesis (P) at ambient CO_2 level. The maximum P of the mutant was only about 50% of that for the wild type. Oscillations of two types were observed: slow oscillations at the shoulder of the CO_2 response curve, and rapid oscillations at high-CO_2 (2000 μL/L), indicating two types of regulation. A study of these oscillatory patterns observed at 2% and 20% O_2 for both genotypes supports the hypothesis that stabilization of the cycle after perturbation involves P_i concentration in the chloroplast. Further fluorescence measurements also support this interpretation.

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

DRAKE, BERT G.

SMITHSONIAN INSTITUTION

FY 1991	250
FY 1990	209
FY 1989	206

09/20/91-09/19/92

Objective. To determine whether elevated ambient CO_2 concentration will affect ecosystem production through increased photosynthesis and reduced respiration; alter species composition; alter relative partitioning of biomass between above-ground and below-ground structures; change carbon and nitrogen concentration in plant tissue; alter decomposition rates; 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 and a data base for modeling the effects of CO_2 enrichment on ecosystem processes.

Approach. Three community types will be investigated over a long term at a salt-marsh research site where elevated CO_2 level will be controlled by small, replicated open-topped chambers.

Acclimation of carbon metabolism and light harvesting to CO_2 will be measured.

- Gas-exchange measurements will be made in situ on attached leaves to determine responses to light, CO_2, and temperature of plants grown in normal ambient and elevated CO_2.
- RuBisCo content and activity will be determined as well as other key enzymes and metabolites of the carbon reduction cycle.
- Photosynthetic electron transport will be measured by fluorescence to determine whether acclimation to elevated CO_2 has increased the plant's capacity for light harvesting.

The effects of elevated CO_2 concentration on ecosystem processes will be measured with nondestructive methods to the extent possible.

- Net ecosystem CO_2 and H_2O exchange will be determined by using the chamber as an open gas-exchange cuvette.
- Biomass production and competition will be determined by a census of shoots and allometric relationships between length and weight and by studying the regrowth of roots into cores.
- Decomposition will be followed in situ with litter bags.
- Tissue analysis for nitrogen, carbon, and other molecular constituents will be used to study nutrient balance.

Results to Date. No results reported.

FREE-AIR CO_2 FIELD ENRICHMENT (FACE) FACILITY DEVELOPMENT

HENDREY, GEORGE

BROOKHAVEN NATIONAL LABORATORY

FY 1991	973
FY 1990	1095
FY 1989	830

10/01/90-09/30/91

Objective. To develop, test, and deploy free air gas delivery systems (FACE) for enriching field crops and natural plant communities to specified levels of CO_2, and to conduct field experiments with cotton at ambient level of 550 ppm CO_2

to obtain physiology, growth, and yield data for validating a plant simulation model, COTCO2.

Product. An experimental facility for maintaining specified levels of CO_2 in plant communities and field data sets for evaluating CO_2 effects on native and agricultural vegetation including physiology, growth, and plant-environment interactions.

Approach. Realistic field data on the effects of increasing ambient CO_2 concentrations on the flux of carbon between the biosphere and atmosphere will be obtained with an open design. Concentrations of CO_2 will be controlled in a free-air setting by regulating the mass flow of pure CO_2 into circular dispersion systems (rings) 22 to 27 meters in diameter. The CO_2 will be prediluted by mixing with ambient air prior to release through 32 independently valved vertical vent pipes (VVP) on each ring. Selection of the VVPs to be opened will be based on wind direction. The mass of CO_2 released will be proportional to wind velocity; flow will be adjusted by closed-loop feedback regulation based on measurements of CO_2 in the center of each ring each second.

Field experiments will produce biological data on physiology, growth, and plant-environmental interactions for ambient- and elevated-CO_2 treatments and for irrigated and water-stressed conditions. Feasibility of the system will also be tested with even-aged stands of trees.

Results to Date. A prototype FACE system was constructed and tested in Upton, N.Y., in 1986. Full-scale experimentation in a commercial cotton field commenced in Yazoo City, Miss., during 1987 and 1988 as a joint research effort with the U.S. Department of Agriculture and several universities. Since the spring of 1989, four replicates, each consisting of a FACE CO_2 enriched treatment plot and a control plot of equal dimensions, have operated in a cotton field at the University of Arizona Maricopa Agricultural Center. During 1990, split-plot irrigation-control equipment was installed to study the effects of water stress in combination with CO_2 enrichment.

Under the specific conditions encountered at Maricopa, Ariz., during the 1989, 1990, and 1991 growing seasons, the FACE system has maintained CO_2 concentrations to within 10% of the 550-ppm setpoint more than 90% of the time and within 20% more than 99% of the time, based on 1-minute averaging. No machine effects have been observed over an area of 350 m^2 in the center of each of the FACE plots (415 m^2 for a 27-m-diam ring). Operating data show that the FACE system is less expensive to operate per unit of experimental plot area than various chamber-based exposure systems.

Gross response of cotton to CO_2 enrichment included reaching marketable yield five weeks early, producing about 50% more biomass (40% more above ground and 76% more below ground), developing longer and denser roots, having 20 to 40% higher rates of photosynthesis, maintaining slightly lower transpiration per leaf, and having 0.8°K-warmer foliage. Soil-water depletion was higher in well-watered, CO_2-enriched plots than in unenriched plots. However, water depletion was the same for enriched and unenriched plots when under water stress.

Leaf photosynthesis (carbon exchange) showed a marked CO_2 effect with high light intensity but not under diffuse light conditions. Early in the season (June-July), mid-day canopy photosynthesis was slightly greater in CO_2-enriched plots. Reduced watering caused a small reduction in photosynthesis in enriched plots, but not in unenriched ones. In August, water treatment had a greater effect on canopy photosynthesis than did CO_2 treatment.

The soil organic carbon was greater in CO_2-enriched plots than in control plots. Neither CO_2 enrichment nor differential watering caused any effect on the available nutrient status of the soil. C/N ratios were higher in enriched plots for both leaves and stems.

No differences between the rhizosphere and nonrhizosphere bacterial populations have become apparent among the CO_2-enriched and unenriched plots. Some effect of elevated CO_2 may be present among some fungal groups in the rhizosphere of the cotton plants.

The large areas and detailed monitoring of the physical and biological variables in the experimental plots have enabled researchers to use this project as a platform for testing new technologies. Remote-sensing techniques that measure the amount of light reflected from the plant canopy in both visible and near-infrared wavelengths are being developed to quantify the effects of CO_2 enrichment and water stress on plant biomass, leaf-area index, and light-use efficiency. In 1991, carbon isotope ratio studies were begun. These studies take advantage of the fact that the CO_2 used for enrichment contains fossil carbon, which has a different isotopic ratio from atmospheric CO_2.

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

KIMBALL, B.

WATER CONSERVATION LABORATORY
and WESTERN COTTON RESEARCH LABORATORY

FY 1991	90
FY 1990	140
FY 1989	176

09/01/91-08/31/92

Objective. (1) To assemble data for use in modifying a plant-growth simulation model that incorporates CO_2 and other climate-variable effects into 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 "feedback inhibition" of photosynthesis and on rates of development and growth of plant organs; and (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.

Product. Primary information on the physiology, growth, and yield of plants, trees, and annual species in relation to increasing atmospheric CO_2, validation data sets for testing the model COTCO2, and data about the interactive effects of CO_2 and temperature on "feedback inhibition" of photosynthesis and about enhancement of growth at higher temperatures.

Approach. Taking advantage of full-sunlight conditions at Phoenix and using temperature- and CO_2-controlled greenhouses, cotton studies will be conducted at two temperatures and two CO_2 concentrations. Switching experiments will examine the occurrence of "feedback inhibition" on photosynthesis [the sometimes-observed phenomenon where the supply of assimilates (related to elevated CO_2 and increased carbon fixation) may exceed demand causing a decrease in photosynthetic capacity]. When inhibition is observed, additional measurements will be taken to investigate intercellular phosphate and O_2 insensitivity of RuBisCo.

The open-topped CO_2-enrichment-chamber technique will be used with ambient and 650 ppm levels of CO_2, and plant physiology and growth will be determined for different temperature conditions. An experiment with citrus will continue to collect data on the CO_2 effects on leaf area, biomass, yield, foliage temperatures, net photosynthesis, stomatal conductance, photosynthetic response to CO_2, leaf carbohydrate content, and stomatal response at variable soil-moisture content.

Because CO_2 enrichment changes the biochemical properties of plant tissue, which in turn influences the feeding habits and rates of foraging of insects, the cotton experiment will furnish plant material for an ancillary experiment to determine how host cotton grown at two levels of CO_2 and two temperatures affects growth of beet armyworm.

Results to Date. An initial version was completed of a new cotton growth model, COTCO2, which should be capable of predicting the effects of the increasing atmospheric CO_2 concentration and any climate change on cotton growth and water use. Sensitivity analysis and validation efforts are commencing.

With the open-topped-chamber approach, continuous exposure of orange trees to CO_2 elevated 300 ppm above ambient has resulted in 100% more branches, 75% more leaves, 160% more trunk and branch volume, and 130% more fine-root biomass than that of control trees at ambient CO_2. Net daytime leaf photosynthesis increased by about 122%, and nighttime leaf respiration decreased by about 63%. Such changes in photosynthesis and respiration account for the large changes in growth.

Screen-topped chambers were used to determine the effect of high-CO_2-grown host cotton on pink bollworms, which are seed-eaters. No effects on growth, development time, or cotton damage were found. These results are consistent with no change in the C:N ratio (nutritional value) of the cotton seed with CO_2 enrichment. And these results contrast with those found earlier with beet armyworm, a leaf-feeder, whose growth was altered markedly by the changing C:N ratio of cotton leaves under CO_2 enrichment.

EXPERIMENTAL STUDIES OF ECOSYSTEM RESPONSES FOR ELEVATED CO_2: INTERACTIONS WITH NITROGEN, WATER, AND SPECIES CHARACTERISTICS

MOONEY, HAROLD A.

STANFORD UNIVERSITY

FY 1991	100
FY 1990	0
FY 1989	0

09/01/91-08/31/92

Objective. To determine whether system-level responses to elevated CO_2 are driven through direct effects on plants and whether the response of plant growth, as elevated CO_2 generates a novel resource balance, can be understood and predicted by how other resources (e.g., water and non-CO_2 nutrients) influence or regulate growth and other processes.

Product. An understanding of the responses of an annual grassland to altered resource balance, with an emphasis on factors controlling the response of the ecosystem to elevated CO_2 (i.e., mechanisms and feedbacks governing system-level above-ground and below-ground production, decomposition, and nutrient cycling).

Approach. In a field study of natural grassland, the whole system will be treated with elevated CO_2 in open-topped chambers; interactions of altered CO_2, nutrients, water, and species composition will be examined with a large array of treatments with artificial microecosystems; isotopically-labeled plant litter will be used to investigate controls on decomposition and nutrient cycling. In greenhouse experiments, resource effects on plant growth, carbon allocation, and tissue chemistry will be investigated. Results will be integrated with linked plant and ecosystem models.

CO_2 EXCHANGE, ENVIRONMENTAL PRODUCTIVITY INDICES, AND PRODUCTIVITY OF AGAVE AND CACTI UNDER CURRENT AND ELEVATED ATMOSPHERIC CO_2 CONCENTRATIONS

NOBEL, PARK S.

UNIVERSITY OF CALIFORNIA AT LOS ANGELES

FY 1991	133
FY 1990	0
FY 1989	0

09/20/91-09/19/92

Objective. To examine the influence of elevated CO_2 concentrations and accompanying environmental changes on net CO_2 uptake and productivity of crassulacean acid metabolism (CAM) plants; to use the environmental productivity index (EPI) to evaluate plant response to the CO_2 enrichment in relation to soil water status, air temperature, and photosynthetic photon flux density; and to examine the molecular basis for interpreting CO_2 effects on CAM plant metabolism.

Product. Fundamental information on CO_2 fixation by the CAM pathway, which approaches the upper bound of CO_2 fixation by vascular plants.

Approach. Experiments with *Opuntia* will investigate the dependence of CO_2 exchange on plant age, and measurements of both transpiration and net CO_2 exchange will determine water-use efficiency. The study will determine if the EPI holds for plants grown at elevated CO_2. The CO_2-enrichment experiments will be conducted outdoors in open-topped control chambers to take advantage of natural lighting and in situ conditions for growing plants.

Molecular studies will involve energy costs and molecular efficiency of the CO_2-fixation process at ambient and elevated-CO_2 conditions. Fundamental energy requirements will be worked out for two enzyme pathways, ribulose-1, 5-bisphosphate (RuBisCo) and phosphenol-pyruvate carboxylase (PEPCase).

The metabolic pathways will be investigated by CO_2 gas exchange and with carbon isotope fractionation.

ELEVATED CO_2 EFFECTS ON WOODY PLANT SOIL SYSTEMS

NORBY, R. J.; LUXMOORE, R. J.; and O'NEILL, E. G.

OAK RIDGE NATIONAL LABORATORY

FY 1991	487
FY 1990	544
FY 1989	265

10/01/90-09/30/91

Objective. To determine whether temperate forest trees increase in growth and carbon storage as the concentration of carbon dioxide in the atmosphere increases; to investigate mechanisms of nutrient cycling in relation to tree-growth change as influence by atmospheric CO_2 concentration; and to compare simulated tree-ring chronologies with field data on forest response to CO_2 increases and develop methods for scaling up soil-plant models in space and time.

Product. Data on effects of CO_2 on tree growth under field conditions; a data base on growth and physiological responses; and new methods of tree-ring analysis that will extend the capabilities for detecting of historical environmental changes on forests and that will provide a definitive framework for assessment studies of CO_2 and climate impacts.

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.

White oak and tulip poplar seedlings will be planted in field chambers, which will be maintained at ambient CO_2, ambient + 150 ppm, and ambient + 300 ppm, with three replicate chambers for each treatment level. The treatments will be maintained during daylight hours for four growing seasons. Above-ground 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 using 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 appearance in the plant will be monitored.

A forest succession model (FORET) will be reformulated into a backcasting mode to predict, backwards in time, tree wood-growth increments for two sites with established tree-ring chronologies. Physiological responses to CO_2 enrichment will be integrated into annual growth increments with the Unified Transport Model. The potential annual increments will be modified by FORET to predict realized annual increment and will be compared with actual tree-ring chronologies.

Methods for applying models to larger space and time scales will be based on a hierarchical structure and will incorporate efficient stochastic procedures for representing parameter heterogeneity. Model outputs will be defined statistically so that confidence intervals for comparison between alternative modeling scenarios can be determined.

Results to Date. During the third field season, photosynthesis per unit leaf area of the yellow poplar and white oak trees was 45 to 52% higher in the +150 treatment and 66 to 70% higher in the +300 compared to the ambient CO_2. Similar enhancements were maintained throughout the second growing season despite increasing leaf age and duration of exposure to CO_2 enrichment. Analysis of the relationship between photosynthesis and internal CO_2 concentration indicted no significant effect of CO_2 treatment on carboxylation efficiency, CO_2-saturated photosynthesis, or CO_2 compensation point. We conclude that no homeostatic adjustment has occurred in leaf-level photosynthesis as has been reported in other systems.

However, leaf area of the yellow poplar trees is lower in elevated CO_2, and this suggests a downward adjustment in canopy photosynthesis. Consequently, the stimulation of above-ground growth in elevated CO_2 is decreasing with time and is not statistically significant. Decreased leaf production may be a result of nitrogen deficiency: foliar nitrogen concentration in the +300 treatment was 15.8 mg/g, compared to 25.5 mg/g in the +0 treatment. Foliar nitrogen concentration was not affected by CO_2 in the white oaks, leaf area is higher in CO_2-enriched trees, and the stimulation of above-ground growth by elevated CO_2 is increasing with time.

RESPONSE OF TUNDRA ECOSYSTEMS TO ELEVATED ATMOSPHERIC CO_2

OECHEL, WALTER C.

SAN DIEGO STATE UNIVERSITY

FY 1991	300
FY 1990	295
FY 1989	244

09/15/91-09/14/92

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 current rates of methane release as a function of vegetation and environment.

Product. (1) A definitive statement of what is known and unknown about tundra response to varying CO_2 and climate conditions and (2) 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/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 CO_2 and CH_4 fluxes with 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, above-ground biomass, carbon content of thaw layer, and depth to permafrost) will be determined simultaneously with the flux measurements. Initial interpretations will relate to CO_2 and CH_4 fluxes to environmental and biotic properties of the systems under observation.

Results to Date. No results reported.

RANGELAND-PLANT RESPONSE TO ELEVATED CO_2

OWENSBY, CLENTON E.

KANSAS STATE UNIVERSITY

FY 1991	292
FY 1990	371
FY 1989	250

09/15/91-09/14/92

Objective. To determine the extent to which the C4-dominated grassland will sequester carbon and act as a buffer against future increases in atmospheric CO_2.

Product. Data on the physiology and plant growth of representative species of the grassland; measurements of carbon fixation and below-ground productivity to provide the basis for estimates of carbon transformation into soil humus.

Approach. Experiments will be conducted in situ in undisturbed prairie.

Above-ground biomass and growth rate of the principal C3 and C4 species (*Andropogon gerardii* and *Poa pratensis*) will be determined by clipping and separating plant material by species and component parts. Below-ground productivity will be determined from root ingrowth into buried sand bags.

Carbon turnover, microbial metabolism, and carbon source/sink relationships will be estimated from measures of soil respiration and decomposition of organic residues (plant and microbial material). Microbial biomass will be determined by fumigation-incubation techniques, and soil respiration will measured by trapping soil-generated CO_2 in mini chambers.

Carbon fixation and water flux will be measured for the intact whole canopy as well as for individual leaves. Leaf-level photosynthesis of the principal C3 and C4 species will be measured in the field experiment on tillers at three canopy heights, supplemented by intensive laboratory studies of acclimation to elevated CO_2 and at controlled light and temperatures.

Isotopic tracer techniques and the Century model will be used in studies of soil organic matter dynamics and for specific estimates of net carbon retention in soil. These data, coupled with observations of CO_2 fixation rates by plants, will provide generic information on the carbon balance of grassland ecosystems and their possible influence on sequestering of atmospheric CO_2.

Results to Date. In 1991, under both high-water (field capacity) and low-water (one-third field capacity) conditions, doubled CO_2 increased canopy temperature (usually by about 2°C, although differences were as great as about 5°C) and reduced canopy evapotranspiration. Under elevated CO_2, canopy photosynthetic rate was increased in the low-water chambers. But in the high-water chambers, photosynthetic rate was often higher under the ambient level of CO_2 than under the doubled level.

Doubled CO_2 increased leaf photosynthetic rate of both big bluestem (*Andropogon gerardii*, Vitman), a warm-season C4 grass, and Kentucky bluegrass (*Poa pratensis*, L.), a cool-season C3 grass. In general, for both grasses, elevated CO_2 reduced leaf transpiration and increased stomatal resistance, intercellular CO_2 concentration, and leaf-water potential. Because transpiration was reduced through stomatal closure, less water was lost from the soil with plants at elevated CO_2 than from the soil with plants at the ambient level of CO_2. Therefore, soil-water content was higher throughout the season in 1990 with doubled CO_2 than with ambient. Similar results were obtained in 1989.

Dry weight of the dominant species on the prairie (warm-season grasses) was not increased with doubled CO_2 when the soil-water level was high. But under the low-water level, the dry weight of the warm-season grasses was increased with elevated CO_2. However, doubled CO_2 never completely compensated for reduction in growth because of drought. Under both high- and low-water conditions, dry weight of roots of plants grown with elevated CO_2 was less than that of roots of plants grown with ambient CO_2.

Between 1989 and 1990, when the same (chambered) area on the prairie was exposed to doubled or ambient CO_2 and to well-watered or dry conditions, the number of C3 species decreased, and the number of C4 species increased. The number of Kentucky bluegrass plants dropped between 1989 and 1990. This might have been caused by the higher temperatures inside the chambers than outside. (The air temperature is always cooler outside than inside the chambers. But, at 100 cm above ground, the chambered plots were usually no more than 2°C warmer than outside.) The higher CO_2 concentration appeared to help Kentucky bluegrass survive, which suggests that doubled CO_2 might be able to reduce death of C3 plants from high temperature.

In 1989, nitrogen was lower, and acid detergent fiber (ADF) was higher in CO_2-enriched plots than in plots with ambient CO_2. Forage quality is lowered when nitrogen is reduced and ADF is increased. The results suggest that with elevated CO_2 animals may eat less and gain less weight because of a decreased forage quality.

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

REYNOLDS, J.

SAN DIEGO STATE UNIVERSITY

FY 1991	451
FY 1990	424
FY 1989	350

09/01/91-08/31/92

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

Product. A suite of plant and ecosystem models that will analyze the combined effects of CO_2 and changing climate conditions and, with these models, the ability to predict plant and ecosystem response to anticipated changes of the future physical environment.

Approach. A leaf model will be developed to 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 continued research will incorporate feedbacks on photosynthesis involving acclimation and carbon- and nitrogen-allocation patterns. Effects of light, temperature, water stress, and leaf age will be incorporated into the leaf model.

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

A whole-plant model will combine canopy and partitioning models into an overall carbon and nitrogen balance for predicting root, stem, leaf, and reproductive growth. The modeling approach will consider resource availability (e.g., photosynthate, nitrogen, and water) and determine potential for growth of organs; this approach will also require knowledge of allocation and biomass partitioning. Patterns of resource availability and allocation determine actual growth; by considering supply-demand relationships, actual growth will be estimated relative to potential.

A community model will link the individual plant to the ecosystem in which it is embedded, and it will examine ways in which species interaction might change as resources (such as CO_2) or other environmental variables (such as temperature) are modified. This mechanistic plant community model will examine multispecies response to CO_2 subsidy as well as to nitrogen, water, and temperature stress. The properties that will be modeled include interspecific competition, nearest-neighbor effects, and resource abundance.

Because the modeling of 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), linkages will be developed among modules and hierarchical relationships for representing interactions.

Results to Date. Additional physiological detail has been incorporated into the leaf model. For example, sensitivity of photosynthesis to both CO_2 and O_2 is reversed when phosphate limits photosynthesis. This reversal has been incorporated into the photosythesis model. Our canopy model was used to investigate the effect of elevated CO_2 on photosynthesis and transpiration of a *Quercus coccifera* canopy, where daily total assimilation increased 50 to 60% and transpiration declined 15 to 25% under short-term exposure to doubled CO_2. A model was developed that considers the allocation of carbon and nitrogen substrates to a protein compartment in the shoots, shoot structural components, and root biomass, allowing variation in shoot-specific activity that could occur because of global change. We also developed a hierarchy of models to study the effects of CO_2 on intra- and interspecific competition in plants. These models reproduce behaviors that are common in plant communities and should prove useful in understanding the complex interactions among species in response to elevated CO_2. Our ecosystem model, SERECO, was further developed and used to simulate the structure and function of three terrestrial ecosystems: grasslands, arid shrubland, and arctic tussock tundra.

WORKSHOP ON PHYSIOLOGICAL ECOLOGY OF CONIFEROUS FORESTS: PAST AND FUTURE

SMITH, WILLIAM K.

UNIVERSITY OF WYOMING

FY 1991	7
FY 1990	0
FY 1989	0

09/20/91/-09/19/92

Objective. To conduct a workshop to prepare a state-of-knowledge review of physiological ecology of coniferous forests and to examine the role of ecophysiology and the future of coniferous-forest biodiversity in the context of global climate change.

Product. A summary and stynthesis of past work and the formulation of questions for future research.

Approach. Leading coniferous-forest scientists from a wide range of countries will address relevant questions about reciprocal relationships of coniferous forests and global change; specifically, the effects of CO_2 on physiology.

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

STRAIN, BOYD R.

DUKE UNIVERSITY

FY 1991	452
FY 1990	391
FY 1989	350

09/15/91-09/14/92

Objective. To examine the direct physiological effects of CO_2 on plants, with emphasis on the long-term effects on the physiology, growth, and ecosystem interactions of loblolly pine.

Product. Data for modeling and predicting changes of plant physiology and growth as a function of different CO_2 and climate conditions, including new experimental information on physiological and ecological controls of whole-plant and whole-system functions.

Approach. Under field conditions, physiological controls on plant response to CO_2 will be examined, with special attention to feedback effects of the plant source-sink carbon balance on CO_2 assimilation rate.

A 2-year partial-factorial-design experiment will be conducted with seedlings and saplings to

determine if limited nitrogen and phosphorous affect loblolly pine's response to increased CO_2. Gas exchange (in terms of the A vs C_1 curve), whole-plant carbon balance, chlorophyll fluorescence, leaf-tissue composition (for CHO, proteins, and nutrients), and RuBisCo activity will be determined as a function of CO_2 treatment.

The studies will be continued for an additional 3 years to achieve long-term data on plant response to increased concentrations of atmospheric CO_2. Measurements will continue with plants that have been "conditioned" by high CO_2; this will allow a realistic and in-depth examination of the degree and mechanisms of how plants photosynthetically acclimate to CO_2. Moreover, plants will be grown in the ground to avoid stresses from root confinement.

Existing information about carbon fixation and allocation in plants will also be assembled. This information will be used to evaluate ecosystem productivity and stability in relation to CO_2 and climate variables, including nutrient availability and cycling, and to assess properties of the ecosystem likely to be affected by CO_2-altered growth (e.g., plant-animal and plant-microbial interactions and water fluxes). This information will be used in reexamining the Farquhar equation and in formulating generic models (e.g., PRECO and SERECO) of whole-plant and whole-system response to CO_2 and climate.

Results to Date. Measurements of biochemical pools of selected enzymes, carbohydrates, chlorophyll pigments, and secondary compounds are being taken to test a source/sink-based hypothesis that seeks to understand the primary controls on carbon acquisition, allocation, and sequestration. Collaborative studies are under way with other investigators to examine insect herbivory and mycorrhizal interactions in the loblolly pine ecosystem. Open-topped chambers are being maintained at ambient and enriched CO_2 levels and at optimal and reduced nitrogen and phosphorous levels within each CO_2 treatment. Plants are periodically measured to determine physiological properties and harvested to determine growth characteristics. With all other environmental factors being optimal, total biomass of plants grown at 150 and 300 ppm CO_2 above ambient increased 51% and 71% above ambient controls respectively. Although growth response to CO_2 was small when soil nitrogen or phosphorus were severely limited, tissue-nutrient analyses indicated significant interactive effects of increased atmospheric CO_2 and soil nitrogen and phosphorus on needle nutrient concentrations. These biochemical effects propagate through the ecosystem to significantly affect herbivores and mycorrhizae.

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 others will be directly affected by CO_2. Additionally, coastal resources may be sensitive to rising sea level and related factors (e.g., changes in tidal regimes). Effects on resources such 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 CO_2-climate change on key resources on a regional basis, (2) to develop useful responses to possible problems, and (3) to develop mechanisms to take advantage of possible benefits introduced by CO_2-climate change. The effects of both CO_2 and climate will be considered, and important interresource 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 CO_2-climate change and to other important factors, such as technology or government/economic actions?
- What additional analysis 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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Research Summaries

WORKSHOPS ON RESEARCH NEEDS

BERNABO, J. CHRISTOPHER

SCIENCE AND POLICY ASSOCIATES, INC.

FY 1991	25
FY 1990	0
FY 1989	0

09/01/91-09/30/91

Objective. To conduct two workshops to identify research needs to address decision makers' uncertainties relating to global climate change.

Product. Identification of the priority information needed by decision makers to respond to the risks of global climate change and of research that is needed to provide that information.

Approach. Under the cosponsorship of EPRI, USDA, EPA, and the National Climate Program, a workshop of government and private-sector decision makers will be convened so they can identify their information needs in order to manage the risks of global climate change; a number of technical white papers will be commissioned from eminent scientists on topics related to the information needs of decision makers; a workshop will be convened so scientists can discuss the white papers and identify the research that needs to be done to meet the information needs of decision makers.

CARBON DIOXIDE INFORMATION AND ANALYSIS RESEARCH PROGRAM: RESOURCE ANALYSIS

CUSHMAN, R., and DANIELS, R.

OAK RIDGE NATIONAL LABORATORY

FY 1991	142
FY 1990	281
FY 1989	450

10/01/90-09/30/91

Objective. To plan, monitor, and produce data sets needed to anticipate and analyze the consequences of changing CO_2 and climate on natural and societal resources.

Product. Evaluations of the response of natural and societal resources to climate-induced changes in the environment brought about by increases in the atmospheric concentration of CO_2; data bases useful for the analysis 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 analyzing the response of resources to changing CO_2 and climate will be investigated, including the definition of regions and climate-change scenarios for use in regional resource analyses. A global coastal-hazards data base containing geologic, geomorphic, elevation, tide, wave height, and local sea level trends will be combined with climatological data (e.g., hurricane and extratropical cyclone frequencies) to identify those areas of the U.S. that are especially susceptible to erosion and inundation. Other data bases will be developed as needed

for specific analyses. Geographic information systems will be applied to the analyses of this subtask.

Results to Date. As part of an ongoing effort to obtain information on coastal zones, data on the frequency and intensity of coastal storms were derived and calculated for the world. This data has been published in *A Global Geographic Information System Data Base of Storm Occurrences and Other Climatic Phenomena Affecting Coastal Zones* (ORNL/CDIAC-40). The climatological data are currently being combined with information in the Global Coastal Hazards Data Base in an effort to identify areas along the U.S. East and Gulf coasts that are at risk from permanent inundation, episodic inundation, and erosion.

Based on the combined climatological and coastal-hazards data bases, coastal-hazard maps for the U.S. East and Gulf coasts have been produced. From these maps, two high-risk areas in the southeast U.S were selected for more detailed study. For each study area, the role of infrastructure and competing land uses was analyzed to determine if the retreat option to sea-level rise is viable. The study areas have been selected to represent resort/residential areas on the Atlantic Coast (the dominant mode of development in the southeast U.S.).

RESOURCE ANALYSIS RESEARCH

EDMONDS, JAMES, and
SCOTT, MICHAEL

PACIFIC NORTHWEST LABORATORY

FY 1991	263
FY 1990	846
FY 1989	700

10/01/90-09/30/91

Objective. To develop the scientific information base and analytic tools needed to describe the nature, timing, magnitude, and uncertainty of the consequences of increasing atmospheric CO_2 and climate change on human and natural systems, including describing direct and indirect effects (e.g., water-resource interactions with the energy system) at the regional level and how regional system changes and responses interact within and between regions.

Product. A coordinated program for the Resources Analysis Research Project; the selection of a region for analysis and the identification of the most important research issues to be addressed; a baseline description of the resources and interactions within the region for today's climate and resources; an analysis of the impact of a historical analog climate on today's resources; and an analysis of the impact of a future climate on projected 21st-century resources.

Approach. Research efforts at Pacific Northwest Laboratory on uncertainty analysis of tiered models, at Oak Ridge National Laboratory on natural and human resource data scaling, and at other participanting institutions will be cordinated. The Pacific Northwest will be the study area. A quantitative analysis of the current relationship between the regional resource base and the economic and social viability of the region will be conducted providing a baseline description of the study region and accounting for such external influences as world agricultural markets and technological change. Workshops and meetings will be conducted and participated in; papers and reports will be published.

Results to Date. The effects of climate change on the MINK region (Missouri, Iowa, Nebraska, and Kansas) with a 1930s analog climate have been investigated. Crop models were run with technological change likely by the year 2030. Longer-season varieties and CO_2 fertilization effects increase above baseline levels the yields of all crops except corn. In the worst case (no CO_2 enrichment and no farmer adjustments), production declines by $5.3 billion or 22% from the 2030 baseline. In the best case, yields increase by $645 million or 3% above the

baseline. Analog climate resulted in a long-term decline in forest inventory and logging. Large carbon taxes might lead to wood-fired electrical power plants in the Ozarks based on short-rotation plantation forestry. Irrigation would likely shrink in Nebraska and Kansas, based on renewable supplies. Irrigation (more profitable under climate change) could increase significantly in Iowa and Missouri. Additional irrigation would increase agricultural energy demand 3% above baseline in the year 2030. If (as is unlikely) the worst-case loss in crop production falls entirely on feed-grain supplies in the region, the effect on total regional output could be almost a 10% loss. In the best case, regional production actually increases with climate change.

GLOBAL CLIMATE AND ACID DEPOSITION ASSESSMENTS

EDMONDS, JAMES A.

PACIFIC NORTHWEST LABORATORY

FY 1991	180
FY 1990	50
FY 1989	0

10/01/90-09/30/91

Objective. To support the USDOE in its development of a National Energy Strategy (NES).

Product. Research, reports, and presentations to DOE in support of the NES chapter on energy and climate change.

Approach. State-of-the-art energy models will be used to prepare analyses of energy and economic cost results, PNL will make presentations to DOE, and the NES chapter on energy and climate change will be generally supported.

Results to Date. No results reported.

INFORMATION AND INTEGRATION

Knowledge is of little use if the persons and organizations needing it are not aware of it or cannot obtain it. In a program like the Carbon Dioxide Research 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 information and integration component of the Carbon Dioxide Research Program provides mechanisms through which scientific information can be obtained, evaluated, and subjected to quality-control procedures; the exchange of data can be promoted and facilitated; and high-quality analyses of complex data can be performed 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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Research Summaries

DESIGN AND ANALYSIS OF LARGE-SCALE ATMOSPHERIC-DISPERSION EXPERIMENTS

BAER, FERDINAND

UNIVERSITY OF MARYLAND

FY 1991	3
FY 1990	0
FY 1989	0

12/01/90-12/31/90

Objective. To publish the paper "A Study of Tracer Distribution Parameter Estimation from Sparse Samples" by J. Z. Holland in the *Journal of Applied Meteorology*.

Product. The published article.

Approach. Submitting the article to the journal for publication.

Results to Date. The paper has been reviewed and recommended for publication subject to shortening and suggested improvements. These revisions have been made, and the revised manuscript has been resubmitted for publication.

CARBON DIOXIDE INFORMATION ANALYSIS CENTER

KANCIRUK, PAUL, and CUSHMAN, ROBERT

OAK RIDGE NATIONAL LABORATORY

FY 1991	1907
FY 1990	1323
FY 1989	1130

10/01/90-09/30/91

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 will identify 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 will be evaluated as to usefulness and, if appropriate, will then be acquired if available or compiled at CDIAC if not in a usable form. These information products will undergo extensive quality assurance and complete documentation in full coordination with the original supplier of the information. They will then be made available to the research and policy-making communities. CDIAC will work 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 policymaking communities by serving as CDRP's information-gathering and distribution center. Activities included obtaining and evaluating data and technical literature; producing numeric data packages (NDPs) and computer model packages (CMPs); and distributing CO_2-related reports. During FY 1991, 10 new or updated NDPs were produced (topics included atmospheric trace-gas concentrations, storm frequencies of occurrence, climate data from China and the Soviet Union, and factors affecting coastal vulnerability to rising sea level). Three issues in the new *DOE Research Summary* series and three editions of *CDIAC Communications* were produced. In addition, CDIAC produced *TRENDS '91: A Compendium of Data on Global Change*, the second in a series of reports that summarizes data related to global change in the areas of CO_2 emissions; atmospheric concentrations of CO_2, CH_4, N_2O, and CFCs; and climate.

Through the third quarter of FY 1991, CDIAC has responded to 442 requests, from 49 countries, for NDPs and CMPs. Since FY 1985, 4572 copies of data sets and models have been distributed. CDIAC has filled 6821 requests from 2781 individuals in 58 countries through the third quarter of FY 1991. This brings CDIAC's total to 27,071 requests from users in 92 countries since FY 1985.

GLOBAL CHANGE EDUCATION

Numerous studies have identified needs for well-trained scientists and engineers to advance progress in science, technology, and global competitiveness. The objective of Global Change Education is to provide education and training of the next generation of scientists involved in all aspects of global change research. The initiative is designed to counter the scientific brain-drain, in which the Nation's top young people are now choosing nonscientific professions.

The initiative seeks to strengthen the human-resource base for the interdisciplinary sciences of global change research. Emphasis is placed on broad training in a wide suite of sciences because the global change problem, like many challenges in industry, is exacerbated by the need for cross-disciplinary training. This initiative is part of the nation's overall program for upgrading scientific skills in energy, environment, and industry.

One aspect is to provide fellowships for scientific skills required for global change research. Nationally, approximately 1000 undergraduate, graduate, and postgraduate fellowships will be awarded at academic institutions in the course of five years. A survey will be carried out with other federal agencies that participate in the US/GCRP to estimate the future needs for scientists in global change research. From these basic data, appropriate undergraduate and graduate fellowships will be awarded on a competitive basis.

Attention will also be given to energy and environmental science curricula for kindergarten through twelfth grade to attract young people to science in general and to point out career opportunities in energy, climate, and global change research. In part, the precollege effort will build on the highly successful pilot study by LLNL and will link with general-science-education initiatives of NSF.

Prestigious fellowships will provide graduate training and post-graduate employment opportunity in the exciting field of global change research. Individuals trained in the interdisciplinary sciences will assure the acquisition of next-generation scientific knowledge. And an intellectual foundation will be provided for solving problems concerning the future integrity of the Earth's physical/biological/social systems. Broad-based education and training will strengthen interdisciplinary approaches while developing skills in problem solving and mathematical modeling.

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Research Summaries

POSTDOCTORAL RESEARCH PROGRAM FOR GLOBAL CHANGE

WOHLPART, A.

OAK RIDGE ASSOCIATED UNIVERSITIES

FY 1991	1904
FY 1990	74
FY 1989	0

10/01/90-09/30/91

Objective. To increase the involvement of scientists and engineers in areas supportive of the U.S. Global Change Research Program.

Product. A larger pool of professionals with the education and experience in global change research necessary for future research and teaching efforts.

Approach. Recent doctoral-degree recipients will receive fellowships to conduct research in support of the U.S. Global Change Research Program as it relates to the specific mission of the U.S. Department of Energy (DOE) and the Committee on Earth and Environmental Sciences (CEES). Fellows will spend up to two years at approved DOE, CEES, and university laboratories conducting research in technical areas related to the interdisciplinary science elements of global change. Fellows will gain access to a valuable combination of outstanding professional staff, scientific equipment and facilities, and ongoing global change research. These fellowships help promote the influx of new ideas and skills into the laboratories, complement and extend the traditional academic research and training programs, and enhance interactions between the academic community and federal researchers.

Results to Date. The Global Change Distinguished Postdoctoral Fellowships were initiated in FY 1991 to provide DOE and CEES laboratories with high-education individuals for advancing the science of global change. Fellowship literature was prepared and distributed to universities and laboratories across the nation, resulting in the receipt of 110 applications. These applicants had received doctoral degrees from more than 55 universities in a wide variety of scientific and engineering disciplines related to global change. A panel was convened to review applications and make recommendations for awards. The panel identified 29 finalists, and DOE announced that 18 fellows had been selected to receive awards. The fellows received their doctoral degrees from 14 universities in such fields as biology, physics, geology, chemistry, oceanography, mathematics, atmospheric sciences, ecology, meteorology, and civil engineering. They were appointed to 14 laboratories, and all will begin their fellowships during 1991. During FY 1991, promotion began for the second fellowship cycle, which has an application deadline of February 15, 1992.

OCEANS RESEARCH

The ocean has a large, but poorly known, capacity to absorb heat from the atmosphere and to sequester it in slowly ventilated subsurface waters. By storing heat, the ocean provides thermal inertia to the climate system, limiting its sensitivity to increased atmospheric levels of greenhouse gases.

Atmospheric CO_2 is absorbed by the surface layer of the ocean and fixed into particles and dissolved matter by biological processes. Mixing and advection of dissolved matter, and to a lesser degree sinking particles, remove carbon from the well-mixed surface reservoir for periods ranging from days to millennia and thereby affect the rate of CO_2 accumulation in the atmosphere.

In a warmer climate, the ocean circulation could be significantly different than it is today. Paleo-oceanographic evidence indicates that reorganization of ocean circulation has occurred since the most recent glaciation. However, most observations and models of the ocean continue to focus on the present state to understand how the ocean operates now.

The ocean is an important component of four major feedback processes in the climate system. (1) With atmospheric water vapor feedback, a warmer troposphere will contain more moisture that may lead to greater radiative forcing than would occur from increased atmospheric CO_2 alone. (2) Because of sea-ice-albedo feedback, less sea ice in a warmer climate would reduce reflection of solar radiation and produce warmer surface temperatures in high latitudes. (3) In the case of cloud feedback, a warmer atmosphere may contain more clouds or clouds with different radiative transfer characteristics than Earth's present cloud cover. (4) In regard to oceanic heat transfer and storage, a warmer ocean with reduced thermohaline circulation may absorb a different amount of heat from the climate system than the ocean does at present.

It is generally agreed that the first two feedback processes are positive (i.e., they amplify the heating caused by the accumulation of radiatively active gases in the atmosphere). The strength of these feedbacks in a future climate system is not known with much confidence largely because of limited knowledge about (1) how sea-surface temperatures will change with increased radiative forcing and (2) the factors controlling the area and volume of annual sea ice. Uncertainty about the last two feedbacks extends even to their signs. Here again, limited understanding of the ocean, specifically cloud forcing in ice-covered regions and the coupling between the surface and deep layers, is largely responsible for the incertitude. These deficiencies and the lack of an acceptable way to predict future oceanic conditions on interdecadal to centennial times scales drive the Carbon Dioxide Research Program to expand its ocean-research program.

Research Objectives. The Program's objectives are to estimate the future climate change resulting from emissions of carbon dioxide from energy use, and to estimate the future emissions of carbon dioxide from energy sources and its concentration in the atmosphere.

To meet its objectives, CDRP will support the acquisition of large sets of ocean data with other agencies through global observation programs. These data are essential for continued improvement and validation of prognostic models of the ocean-atmosphere system and the

carbon cycle. The programs that may supply these data are the World Ocean Circulation Study (WOCE) and the Global Ocean Flux Study (GOFS). The primary data-acquisition effort will be to support the global survey of ocean CO_2 in conjunction with the WOCE Hydrographic Program.

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Research Summaries

EFFECTS OF WHITECAPS ON THE AIR/SEA CO_2 EXCHANGE

ASHER, W. E.

BATTELLE MARINE SCIENCES LABORATORY

FY 1991	530
FY 1990	356
FY 1989	150

10/01/90-09/30/91

Objective. To develop a method for prediction of air/sea gas-transport velocities from passive microwave radiometric measurements of oceanic whitecap coverage.

Product. An empirical parameterization of air/water gas-transport velocities in terms of fractional whitecap coverage and molecular diffusivity developed from laboratory experiments; a test of the empirical parameterization with measurements of oceanic whitecap coverages and in situ gas exchange; and a relationship between apparent microwave-brightness temperature of the ocean surface and fractional-area whitecap coverage.

Approach. The main goal is to be able to predict the air/sea gas-transport velocity, k_L, from remote measurements of the fractional-area whitecap coverage, W_c. Because it may be possible to determine W_c from satellite measurements of the microwave-apparent brightness temperature of the sea, correlation of k_L with W_c may allow prediction of k_L with the spatial coverage necessary for calculating global CO_2 fluxes. To develop this remote-sensing-based method of determining k_L, the Battelle Whitecap Simulation Tank (WST) will be used to develop an empirical model for prediction of k_L from fractional-area bubble-plume coverage, F_c; molecular diffusivity, D; and aqueous-phase solubility of the gas. Study of carbon dioxide, oxygen, helium, sulfur hexafluoride, and dimethyl sulfide will allow parameterization of k_L in terms of F_c and D.

Two field experiments will be conducted as part of this research program. A ship-based deliberate dual-tracer gas exchange/whitecap coverage experiment will be performed. And an aircraft-mounted video camera and microwave radiometer will be used to simultaneously measure microwave-apparent brightness temperature and whitecap coverage over Nantucket Shoals. As part of this experiment, data will also be collected during overflights of the satellite-mounted Special Sensor Microwave/Imager (SSM/I) radiometer.

Results to Date. A simple model for the relation of fractional-area whitecap coverage and molecular diffusivity to k_L has been developed from gas-exchange experiments in the WST with oxygen, helium, sulfur hexafluoride, and dimethyl sulfide. In agreement with current models for bubble-plume-driven air/water gas exchange, these experiments have shown that the diffusivity dependence of k_L decreases from $D^{1/2}$ to $D^{1/3}$ as F_c increases from 0.0 to 0.6%. In contrast with these models however, the WST data for the gases studied does not indicate that k_L is correlated with aqueous-phase solubility. These results will be of importance in analysis of the Atlantic Ocean dual-tracer gas-exchange data. Further tests of existing bubble-governed air/water gas transport models will be facilitated by the installation of a laser phased doppler anemometer (LPDA) in the WST.

Preliminary analysis of the data from the Nantucket Shoals aircraft experiment indicates that increasing whitecap coverage is correlated

with increasing microwave-apparent brightness temperature. This result indicates it may be possible to correlate brightness temperature with W_c and, therefore, with k_L.

CO_2 MEASUREMENTS ALONG THE WOCE P-16 AND P-19 SECTIONS IN THE SOUTH PACIFIC OCEAN: A JOINT LDGO/WHOI PROGRAM

BREWER, PETER G.

WOODS HOLE OCEANOGRAPHIC INSTITUTION

FY 1991	320
FY 1990	150
FY 1989	0

10/15/90-10/14/91

Objective. To contribute accurate data on the carbon chemistry of seawater to a global oceanic data base for numeric modeling.

Product. Tabulated carbon-chemistry properties of Pacific Ocean seawater and an evaluation of the compatibility of total CO_2 and alkalinity measurements made by different methods.

Approach. Three carbon-chemistry properties will be measured in seawater from the Pacific Ocean along the WOCE P-16 and P-19 lines. Measurements of total CO_2, total alkalinity, and partial pressure of CO_2 from at least one-third of the 440 sampling stations will yield profiles of carbon chemistry with depth in the Pacific Ocean. At least two samples of the surface mixed layer will be analyzed at every station. Aboard ship, total CO_2 will be measured with a coulometer, and total alkalinity analyses will be performed with an automated potentiometric system. A number of samples will be analyzed for total CO_2 by both the coulometric and manometric methods to resolve disagreement between the methods and to evaluate the compatibility of coulometric and manometric total CO_2 data. CO_2 partial pressure will be determined aboard ship with an equilibrator/gas-chromatograph system. Some seawater samples will be stored for onshore total-alkalinity determinations by potentiometric acid titration. If possible, the CO_2-chemistry data sets will be produced in a gridded format for numeric modeling. Because virtually no carbon measurements exist for either the surface or deep water of these areas of the Pacific Ocean, the total CO_2, pCO_2, and alkalinity measurements to be made during this project will fill an important data gap.

Results to Date. The first evaluation of the compatibility of total CO_2 measurements made by two methods (coulometry and manometry) has been completed. The work was part of an interlaboratory comparison exercise; the measurements were performed onshore on replicate seawater samples prepared and provided by A. Dickson from the Scripps Institution of Oceanography. To best perform these measurements, we developed a new calibration procedure for total CO_2 measurements by coulometry. This method proved to be reliable, and the results were within the standard error of the measurement of both manometric and coulometric techniques.

Overall, the results of the interlaboratory comparison show that the compatibility of total CO_2 measurements with different methods has been achieved by some laboratories and, consequently, can be achieved by all laboratories by following specific procedures. The description of these procedures (*DOE Handbook of Methods for the Analysis of the Various Parameters of the Carbon Dioxide System in Sea Water*) is now close to completion and will be distributed to the CO_2 scientific community.

STEADY-STATE AND TRANSIENT MODELING OF TRACER AND NUTRIENT DISTRIBUTIONS IN THE GLOBAL OCEAN

BROECKER, W. S.

COLUMBIA UNIVERSITY

FY 1991	129
FY 1990	0
FY 1989	0

08/01/91-07/31/92

Objective. To diagnosis the time-dependent relationship between ocean circulation and biological activity relative to the ocean carbon cycle.

Product. New information on and a tool to explore the transient behavior of the interactions among ocean circulation, biological activity, and the carbon cycle.

Approach. A 2-D zonally averaged ocean model will be extended to include ocean tracers and nutrients. Inclusion of the ocean tracers will assist in the validation of the model and the diagnosis necessary to improve the model's capabilities. The transient behavior of the tracer distributions will be analyzed. This transient calculation will include the interaction of the ocean circulation and tracer/nutrients as greenhouse-gas-induced climate change progresses and over paleoclimate time scales.

Bomb-tritium data will be used to constrain the model's dynamics and parameterizations. To capture possible mode changes, the glacial-to-interglacial time scale will be investigated. The model will then be used to study two scenarios for CO_2-induced warming and for a set of experiments to simulate the CO_2 change at the termination of the most recent ice age. Further, the nutrient cycle will be incorporated into the model and validated. The completed model will then be used to identify the physical processes governing the ocean uptake of CO_2. This information will be used to tune the nutrient/physical interactions within the model. Dissolved-oxygen experiments will be used as a final check on the model before conducting experiments and analyses to characterize how the dynamics of the ocean influence the nutrient cycle during climate change.

DEVELOPMENT OF OCEANIC DEEP-CONVECTION MODELS FOR CLIMATE RESEARCH

DENBO, D. W., and SKYLLINGSTAD, E. D.

BATTELLE MARINE SCIENCES LABORATORY

FY 1991	234
FY 1990	262
FY 1989	0

10/01/90-09/30/91

Objective. To design and test a numeric model of open-water deep convection in the ocean and to apply the model to the development of improved parameterizations in future ocean models used for climate studies.

Product. A numeric model of deep oceanic convection, validated with laboratory and field data and including the important processes.

Approach. A 2-D model will be developed to test numeric techniques and to examine the ability of a 2-D model to accurately simulate deep convection. The 2-D model will be validated by comparing nondimensional statistics, such as the wave-number spectra and heat flux, to laboratory data and atmospheric-mixed-layer data reported in the scientific literature. These comparisons will determine if the subgrid-scale turbulence model is properly adjusted, and they will test if the resolved eddy structure is realistic.

The 2-D model will then be used to simulate deep convection with initial conditions from

measurements in oceanic regions where convection occurs. The first of these simulations will use vertical temperature and salinity profiles taken in the Greenland Sea to analyze the structure and evolution of convective plumes in waters where the vertical structure of temperature and salinity support thermobaric effects. The model will be used to examine the increase in mixing caused by the thermobaric plumes by comparing the nondimensional vertical heat flux to cases without thermobaric effects.

The model will also be applied to in the Medoc region of the Mediterranean Sea with the initial conditions observed prior to the seasonal Mistral cold period and a surface heat flux derived from observations. This simulation will run for approximately 20 simulation days. The model vertical profiles of temperature and salinity will be compared to measurements taken at the end of the 20-day cooling period to test the ability of the model to simulate convection when thermobaric processes are not significant.

The model will be converted to three dimensions at the conclusion of the 2-D convection experiments to correctly simulate the influence of rotation, surface wind stress, and vertical current shear. Early testing of the 3-D model will use laboratory tank experiments of convection on a rotating plane that have recently been reported.

Results to Date. Comparison of the 2-D model statistics to observations shows that the spectra of 2-D eddies tend toward a large-eddy bias. Otherwise, the model performs well when compared to measurements of atmospheric and laboratory mixed-layer growth. The effects of rotation and shear could not be examined with the 2-D structure. Preliminary simulations of the Greenland Sea convection demonstrate that thermobaric instability leads to a plume-like structure not observed in simple-mixed-layer cases. The Medoc simulation shows mixing to a depth comparable to observations, with the vertical structure agreeing with measurements of temperature and salinity.

CERTIFIED REFERENCE MATERIALS FOR CO_2 MEASUREMENTS IN SEAWATER

DICKSON, ANDREW G.

SCRIPPS INSTITUTION OF OCEANOGRAPHY

FY 1991	62
FY 1990	95
FY 1989	0

08/01/90-07/31/91

Objective. To ensure consistency among CO_2 measurements made by several teams; to provide continuous intercalibration of instrumentation over the seven-year life of the Global Survey of Carbon Dioxide in the Ocean; specifically, to produce, certify, and distribute seawater reference materials (CRMs) to monitor the performance of coulometers used to measure dissolved inorganic carbon (DIC) in seawater samples.

Product. Certified reference materials and a report documenting the methods for their production, certification, and distribution.

Approach. Two batches of low-nutrient seawater collected from off the coast of California will be filtered and sterilized and adjusted to low (1800 to 1900 micromole/kg) and high (2250 to 2400 micromole/kg) DIC concentrations by gaseous CO_2 injection. In addition, two batches of aqueous sodium bicarbonate solution with pH and ionic strength equivalent to 34 to 35 parts per thousand salinity will be prepared and adjusted to low (1800 to 1900 micromole/kg) and high (2250 to 2400 micromole/kg) DIC concentrations. These materials will be analyzed by standard methods to certify salinity, total alkalinity, and DIC and then preserved in 0.5-L glass bottles suitable for long-term storage.

The bottled CRMs will be distributed to scientists participating in the DOE, JGOFS, and

NOAA ocean-carbon-chemistry observation programs. A system will be designed and implemented to monitor the chemical stability and effective use of these materials during the global carbon dioxide survey.

Results to Date. In FY 1991, more than 2000 half-liter units of seawater and sodium bicarbonate CRMs were bottled in eight batches and distributed to CO_2 analysts in the U.S. and abroad. Each batch was certified for the total DIC by the precision-manometric technique. Analyses of several batches of the bottled material indicated that bacterial contamination may adversely affect the stability of the CRMs. The sterilization, filtration, and poisoning protocols are being modified to reduce the risk of future contamination and to prolong shelf life. Production and bottling capacities have been improved and are now adequate to supply the needs of participants in the DOE CO_2 survey in FY92.

CARBON DIOXIDE OCEAN RESEARCH

DOWNING, JOHN P.

BATTELLE MARINE SCIENCES LABORATORY

FY 1991	438
FY 1990	287
FY 1989	180

10/01/90-09/30/91

Objective. To provide technical and scientific assistance to the Carbon Dioxide Research Program (CDRP) for coordination of the global survey of carbon dioxide in the ocean (SRGF 89-7A), Small Business Innovative Research on advanced sensing technologies for ocean measurements, and process studies for improved ocean circulation models for climate research.

Product. Technical reports and memoranda to assist the CDRP with CES and interagency coordination of ocean research, draft research plans, and a framework for analysis of data streams from large, multi-agency ocean observation programs to meet CDRP objectives in the 1990s .

Approach. Ocean research will include process studies, data analysis, and ocean model development designed to improve existing ocean simulation and prediction capabilities. These activities are conducted in anticipation of large multiagency ocean observations to be conducted in the 1990's such as the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS). The results will provide a better framework to analyze the large data streams expected over the 5- to 10-year expected lives of these programs.

Results to Date. In FY 1991, CO_2 measurements were made on four WOCE hydrographic survey lines, two in the Atlantic Ocean (A9 and A1E) aboard the German Research Vessel F/S Meteor, and two in the Pacific Ocean (P16 and P17) aboard the R/V Thomas Washington. More than 5500 water samples were analyzed for total dissolved inorganic carbon, and other parameters including CO_2 partial pressure, alkalinity, and pH. Certified reference materials (CRMs), provided by DOE, were used for quality control of analyses performed at sea, and 220 replicate water samples were analyzed ashore for total CO_2, by precision manometry, and alkalinity. Fifteen laboratories in Europe and North America performed replicate analyses of CRMs provided by DOE to complete Phase I of an coulometer-intercomparison experiment. The results are being used to evaluate the benefits of using CRMs to ensure CO_2 data consistency during future surveys and long-term monitoring efforts. Five automated coulometers for determining dissolved inorganic carbon content of seawater were provided to participants in the global survey, NOAA, and for analysis of water samples from the Bermuda Atlantic Times Series Station.

Field testing of new sensors for measuring pH and optical properties of the ocean were

successfully completed for the conclusion of three Phase-II Small Business Innovation Research (SBIR) grants. Four new SBIR Phase-I grants to develop particle-flux and chemical sensors began this year as part of the DOE thrust to develop improved, low-power, and autonomous sensors for obtaining ocean chemistry and optical measurements in remote regions.

COULOMETER-INTERCOMPARISON EXPERIMENT

DOWNING, JOHN P.

BATTELLE MARINE SCIENCES LABORATORY

FY 1991	30
FY 1990	50
FY 1989	0

10/01/90-09/30/91

Objective. To determine the consistency of dissolved inorganic carbon (DIC) analyses made by coulometers operated by the shipboard teams participating in the global survey of carbon dioxide in the ocean.

Product. A report and journal article describing the results of the intercomparison experiment.

Approach. A blind test will be conducted with twenty-four 0.5-L bottles of seawater reference materials (CRMs), low-nutrient seawater, collected from off the coast of California, which has been filtered, sterilized, and adjusted to low-DIC (1800 to 1900 micromole/kg) and high-DIC (2250 to 2400 micromole/kg) concentrations by gaseous CO_2 injection. They will be certified for DIC, titration alkalinity, salinity, and pH by standard methods prior to distribution to participants, and will be analyzed at the rate of two bottles per day. A dockside test will then be conducted wherein participants perform analyses on seawater samples at a remote location. This procedure will evaluate the consistency of DIC measurements made under field conditions and will allow the teams, operating under like conditions, to observe and learn from each other. The DIC measurements will then be made at sea aboard a research vessel. It is envisioned that this phased approach will effectively reveal both instrumentation and operator problems at an early state of the global survey and provide a vehicle for their early correction.

Results to Date. Fifteen laboratories in North America and Europe were each provided with a case of CRMs to analyze for total DIC. The data are currently being interpreted to evaluate the potential benefits of using CRMs during the remainder of the oceanic CO_2 survey. The results have been reviewed by the CO_2 Science Team and will be released as a technical report in the coming year. In preparation for the dockside experiment, five automated coulometers for CO_2 analysis of seawater were assembled and tested by Brookhaven National Laboratory (BNL) and provided to participants in the global CO_2 survey, NOAA, and scientists conducting CO_2 measurements at the Bermuda Atlantic Times Series Station. A five-day training course on CO_2 coulometry was conducted by BNL to familiarize coulometer recipients with the new instruments. Eleven analysts attended the course from the following institutions: Atlantic Oceanographic and Meteorological Laboratory (NOAA), Pacific Marine Environmental Laboratory (NOAA), Scripps Institution of Oceanography, Lamont-Doherty Geological Observatory, University of Maryland, Pacific Northwest Laboratories, and the Bermuda Biological Station for Research.

MIXED-LAYER MODEL

EMERSON, STEVEN

UNIVERSITY OF WASHINGTON

FY 1991	72
FY 1990	67
FY 1989	0

08/01/91-07/31/92

Objective. To understand the utility of chemical tracers for determining biological fluxes in the ocean by using an ocean mixed-layer model incorporating chemical tracers and an ecosystem paradigm.

Product. An upper-ocean model for interpreting the time series of temperature, salinity, nutrients, ^{14}C primary productivity, chlorophyll, dissolved organic and inorganic carbon, and particle fluxes being acquired at the JGOFS station north of Hawaii.

Approach. A mixed-layer model of the Price-Weller-Pinkle type will be used to reproduce the density field observed at Station P in the subarctic North Pacific Ocean. To this model, an ecosystem structure, including mechanisms for nutrient cycling, will be added to relate mass fluxes of metabolic constituents to observable biological quantities. Gas-exchange rates at the air-water boundary of the model will be verified by reproducing measurements of the inert gases N_2, Ar, and ^{222}Rn. With calculated nutrient fluxes and air-water gas-exchange rates from the model, mixed-layer oxygen and CO_2 concentrations are potential measures of new biological production. Once the model performs well for Station P, it will be applied to the data from the JGOFS time-series station near Hawaii.

Results to Date. No results reported.

DIAGNOSTIC ANALYSIS OF IRON LIMITATION OF CO_2 UPTAKE BY OCEANIC PHYTOPLANKTON

FALKOWSKI, PAUL G.

BROOKHAVEN NATIONAL LABORATORY

FY 1991	107
FY 1990	0
FY 1989	0

12/01/90-09/30/91

Objective. To develop a diagnostic technique to determine iron limitation of phytoplankton production.

Product. The ability to quantitatively assess any iron or other trace-metal nutrient limitation in subarctic and Antarctic surface ocean waters.

Approach. The research will use a variety of techniques, including biophysical, biochemical, and molecular, to assess the effects of iron deficiency on phytoplankton. Controlled laboratory studies, using iron-limiting cultures, will provide basic information on the response of the photosynthetic apparatus to iron limitation. Intraspecific comparisons will be made between phytoplankton from several taxonomic groups. Field studies with natural phytoplankton populations in the Southern Ocean will be conducted to determine whether natural iron concentrations limit phytoplankton biomass and productivity.

Results to Date. The primary focus of this project has been to develop a means of not only identifying but also interpreting internal physiological processes or "diagnostic signals" that reflect an external environmentally imposed limitation. We have investigated how fluorescence signals are affected by iron limitation in a variety of cultured phytoplankton. The approach uses the pump-and-probe fluorescence technique, in which the change in the quantum yield of fluorescence of a weak probe flash is measured before and following an actinic-pump flash. The results of this work reveal that maximum fluorescence yields and the decay of the maximum fluorescence yield are markedly reduced in iron-limited relative to iron-replete cultures. The potential for using molecular markers to increase the specificity of the diagnostics of iron limitation was also investigated. Based on work done under controlled laboratory conditions, a number of proteins that are important in photochemical activity exhibit iron-induced modifications in relative abundance. Although still in the early stages of development, the use of biophysical

and molecular diagnostic markers should provide more-rapid and less-equivocal information to identify what limits primary production in natural waters.

SUPPORT FOR ACTIVITIES OF THE OCEAN STUDIES BOARD

KATSOUROS, MARY HOPE

NATIONAL ACADEMY OF SCIENCES

FY 1991	50
FY 1990	40
FY 1989	0

08/15/91-08/14/92

Objective. To provide scientific leadership and guidance to the government on important national and international issues in the ocean sciences.

Product. Guidance to the Carbon Dioxide Panel on the issues of oceanic CO_2 measurements, calibration, and data; CO_2 gas exchange across the air-sea interface; seawater CO_2 standards; management of oceanic CO_2 data; and the convening of a workshop on the topic of the exchange of CO_2 across the air-sea interface. Guidance to the Committee on the Ocean's Role in Global Change in issuing a report on the geological elements of global change. Liaison between the U.S. marine research community and the international Committee on Climatic Change and the Ocean (CCCO).

Approach. The Ocean Studies Board (OSB) serves as the National Research Council's focal point for the consideration of ocean issues and will identify, address, and develop studies on appropriate science and policy issues as well as respond to specific requests from federal agencies and private foundations.

The OSB is comprised of 18 regular members and 4 liaison members. It meets approximately three times a year to review its activities, to provide a forum for presentation and discussion of information about federal oceanographic R&D programs, to identify issues needing scientific input, and to assist in the development of U.S. positions on international ocean-science matters.

The Board is a multidisciplinary body with members from physical oceanography, marine ecology and geophysics, marine biology, marine chemistry, and social sciences. The OSB conducts much of its work through committees, working groups, and panels. Members are drawn from academic institutions, industry, and national laboratories.

Results to Date. No results reported.

OCEANIC CO_2 MEASUREMENTS FOR THE WOCE HYDROGRAPHIC SURVEY IN THE PACIFIC OCEAN, 1990-1991: SHORE-BASED ANALYSIS

KEELING, CHARLES D.

SCRIPPS INSTITUTION OF OCEANOGRAPHY

FY 1991	261
FY 1990	361
FY 1989	0

06/01/91-05/31/92

Objective. To conduct shore-based measurements of dissolved inorganic carbon (DIC) and of titration alkalinity on approximately 10% (1400) of the seawater samples collected along WOCE/HP lines P-16 and P-19 in the equatorial and southern Pacific Ocean.

Product. Data tables and plots as well as data in a machine-readable form.

Approach. Seawater samples will be collected, many in duplicate, and preserved aboard ship. On shore, the samples will be analyzed by the

CO_2 Research Group at Scripps Institution of Oceanography. Precise and rigorously calibrated measurements will be made of DIC by manometric analyses and of alkalinity by potentiometric titration. The manometric carbon analysis will be compared to results of shipboard coulometric analysis. Where possible, shore-based alkalinity measurements will be compared to shipboard measurements of alkalinity at the time of collection. Values of CO_2 partial pressure will be calculated with measured DIC and alkalinity as well as with salinity, temperature, and nutrient data. The calculated CO_2 partial pressures will be compared to direct shipboard measurements of CO_2 partial pressure (by equilibration/gas chromatography). The combined shore data and shipboard measurements of carbon chemistry will provide the data base necessary for improving estimates of CO_2 cycling in the ocean.

Results to Date. No results reported.

OCEANIC CO_2 MEASUREMENTS FOR THE WOCE HYDROGRAPHIC SURVEY OF THE PACIFIC OCEAN: SHIPBOARD ALKALINITY ANALYSES DURING 1991 AND 1992

KEELING, CHARLES D.

SCRIPPS INSTITUTION OF OCEANOGRAPHY

FY 1991	97
FY 1990	0
FY 1989	0

02/01/91-01/31/92

Objective. To conduct shipboard measurements of titration alkalinity on seawater samples collected along WOCE/HP lines in the equatorial and southern Pacific Ocean and to use the resulting data in conjunction with pCO_2, DIC, and shore-based alkalinity measurements.

Product. Internal consistency and reliability of oceanic CO_2 data.

Approach. Titration alkalinity of seawater samples obtained along WOCE lines in the Pacific Ocean will be determined at sea by potentiometric acid titration. The alkalinity titrations will be made in conjunction with measurements of dissolved inorganic carbon (DIC) by other DOE-supported shipboard teams. The alkalinity data will be compared with underway measurements of CO_2 partial pressure made by equilibrator/gas chromatography and with shore-based DIC and alkalinity measurements on replicate water samples. The combined data set will provide a critical test of the thermodynamic equations used to connect pCO_2, DIC, and alkalinity.

ACOUSTIC GLOBAL WARMING FEASIBILITY EXPERIMENT

MUNK, W.; SPINDEL, R.; and BIRDSALL, T.

SCRIPPS INSTITUTION OF OCEANOGRAPHY, UNIVERSITY OF WASHINGTON, and UNIVERSITY OF MICHIGAN

FY 1991	200
FY 1990	250
FY 1989	0

04/16/91-04/15/92

Objective. To test the feasibility of ensonifying a global array of underwater hydrophones with a single acoustic source to measure the rate of warming of the global ocean. Specifically, to test signalling schemes and acoustic-path reliability.

Product. A new characterization of long-range acoustic transmissions in the oceanic sound channel, determination of optimal signaling schemes, and analysis of ray-path structure, travel times, and ocean temperature.

Approach. Direct atmospheric measurements of surface warming are difficult because of wide fluctuations in the ambient background air temperature. In contrast to the atmosphere, oceanic temperature fluctuations caused by mesoscale, seasonal, and decadal variations are much reduced, suggesting a robust environment for detecting long-term global-temperature trends. The basis of this experiment is the idea that travel time of acoustic energy between a source and a receiver depends on the sound speed, which in turn is determined primarily by water temperature.

For this test, acoustic signals will be transmitted for seven days from a location near Heard Island in the south Indian Ocean to receivers off the eastern and western coasts of the United States, each a distance of about 16,000 km, and to receivers in New Zealand, Christmas Island, and possibly Mawson Station in Antarctica to determine whether received signal-to-noise levels are sufficiently high to measure arrival times to a required 10- to 20-ms precision. The impact of the signal on marine mammals will also be studied.

Results to Date. The test transmissions from Heard Island were monitored at 15 stations, with 9 countries participating. The signals were received at 14 stations, including stations on both sides of North America.

The experiment determined that electrically driven (rather than explosive) sound sources could transmit signals of sufficient intensity to be received over distances of the order of 10^4 km, that the coded message in these phase-modulated signals could be deciphered by phase-coherent analysis, and that all this could be done without damage to marine mammals in the area of the sources.

Analyses in the frequency domain reveal the transmitted spectra with up to 35-dB signal-to-noise ratios. This is particularly clear with regard to the CW 57-Hz transmissions, and the Pentaline (5 lines) code. The westward transmissions, especially those received at Ascension Island and Bermuda look like laboratory spectra. We have measured phase-coherent arrivals with durations up to 20 minutes. With regard to damage to marine mammals, the 3 Australian and 9 U.S. biological observers are in the process of analyzing the data, but there is no evidence for a behavioral change associated with the acoustic transmissions.

There are some surprises. Passage from Heard Island through the Tasman Sea was observed by New Zealand acousticians, but the transmission appears to be blocked beyond, probably the result of the rough bottom terrain.

OCEANIC UPTAKE OF CARBON DIOXIDE

PENG, T.-H

OAK RIDGE NATIONAL LABORATORY

FY 1991	107
FY 1990	0
FY 1989	0

03/01/91-09/30/91

Objective. To improve the quantitative understanding of atmosphere-ocean CO_2 interactions.

Product. An estimate of the potential for the world oceans to assimilate increases in atmospheric CO_2 during the next century.

Approach. To determine the dynamic constraints on CO_2 uptake by an iron-fertilized Antarctic Ocean, an iron-fertilized Antarctic Ocean with dynamic considerations based on the distribution of bomb-produced ^{14}C will be modeled and simulated in cooperation with W. Broecker, Lamont-Doherty Geological Observatory.

The seasonal variation in pCO_2 and its effect on global CO_2 uptake will be determined. The

measured difference between ocean-surface pCO_2 and atmospheric pCO_2 represents the thermodynamic potential for driving the transfer of CO_2 gas across the sea-air interface. Unfortunately, data describing the distribution of pCO_2 is limited to a small fraction of the world oceans. Previous research used sea-surface temperature to estimate pCO_2 values under various oceanographic regimes. Recent measurements of seasonal variation in sea-surface properties near Iceland, combined with model results for seasonal pCO_2 values, demonstrate that variations in surface pCO_2 are more strongly correlated to nutrient concentrations than water temperatures. To improve upon the previous estimates, it may be possible to exploit relations between spatial oceanic estimate of pCO_2 and existing nutrient-concentration data. Nutrient concentrations in the surface mixed layer are routinely measured during most oceanographic expeditions. One likely potential nutrient surrogate is the oceanic-surface PO_4 concentration. These measurements have been widely made. Thus, the approach entails establishing regional relationships between pCO_2 and PO_4 for the world oceans in collaboration with LDGO, which stores most of the world ocean pCO_2 data. Winter and summer maps of the global distributions of ΔpCO_2 will be constructed. These maps will be used to refine the calculations of net CO_2 uptake by the world oceans.

Results to Date. The proposition was put forward that, if the nutrient-rich Antarctic surface water could be successfully fertilized with dissolved iron, the organic particulate resulting from enhanced production would sink to the deeper water, and the dissolved total CO_2 in the surface water would be diminished. This process would reduce the pCO_2 in surface water and allow the ocean to absorb more carbon from the atmosphere. We developed an advection-diffusion box model with dynamical constraints derived from tracer distributions to test this iron-fertilization hypothesis. To evaluate the possible increase in atmospheric CO_2 with and without fertilization, we used a "business-as-usual" scenario of anthropogenic-CO_2 emission proposed by the Intergovernmental Panel on Climate Change. Assuming a completely successful iron fertilization, we found that within considerable dynamic limits, the reduction ranges from 3% to 12% of the atmospheric pCO_2, with the most likely case of an 8% reduction when the Antarctic upwelling flux of 17.4 Sv is transferred to the deep ocean. Hence, if the atmospheric pCO_2 reaches 800 microatmospheres in the next century, iron fertilization would reduce atmospheric pCO_2 by only 64 microatmospheres. These results are obtained under the assumption that iron fertilization works perfectly over the entire Antarctic Ocean continuously over the next 100 years. It is certain that iron fertilization would not be 100% efficient, and it would not be possible to fertilize the entire Antarctic Ocean continuously at all seasons. Under these circumstances, the atmospheric pCO_2 reduction would be much smaller. It is apparent that iron fertilization in the Antarctic Ocean alone would not reduce atmospheric CO_2 content significantly over the next century.

SEMINAR: OCEAN SCIENCE AND NATIONAL SECURITY

RIGGS, SALLIE K.

WOODS HOLE OCEANOGRAPHIC INSTITUTION

FY 1991	20
FY 1990	0
FY 1989	0

10/15/90-10/14/91

Objective. To provide a basic understanding of the oceans to policy-makers concerned with issues of responsible waste disposal, environmental protection, ocean use, and global climate change.

Product. An understanding by policy-makers of the science that underlies informed decision making.

Approach. A seminar will be conducted at the Woods Hole Oceanographic Institution on October 18-20, 1990. The first and second sessions will serve as an introduction to the oceans, dealing with such fundamentals as size, depths, circulation, geography of the bottom, currents, and temperatures, all leading to an understanding of the role of temperature and mass in global climate change.

The third session will introduce ocean dynamics in terms of biological, geological, and chemical processes; terrestrial inputs; hydrothermal activity; etc. The next session will continue the discussion of ocean dynamics and will conclude with a discussion of the interaction between ocean processes and weather, climate, and pollution. The last session will discuss the diversity of habitats in the oceans and will provide information about how human interaction with the ocean affects individual animals.

A wrap-up discussion will integrate the knowledge gained and relate it to such national-security concerns as defense and antisubmarine warfare, climate change and environment, ocean use and protection, and economic competitiveness.

OCEAN SURFACE-LAYER DYNAMICS

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BATTELLE MARINE SCIENCES LABORATORY

FY 1991	188
FY 1990	100
FY 1989	0

10/01/90-09/30/91

Objective. To determine, by numeric experiments on surface-layer dynamics, if a more detailed treatment of surface-layer processes will substantively change climate and atmospheric CO_2 projections based on simple mixed-layer models.

Product. A numeric model of the turbulent dynamics of the surface mixed layer that will integrate existing field measurements and provide insight into the role of quantities that cannot be directly measured.

Approach. A 2-D model of the ocean surface layer for future conversion to a 3-D model will be developed and tested. The model development will be performed in parallel with the Ocean Deep-Convection project. Following the validation phase of the model development, tests of the model will be performed with measurements at three locations. The first test will examine the model performance during conditions of weak surface wind stress and vertical current shear, but with strong surface cooling. This test will use data obtained near the Bahamas during winter when a well-developed surface mixed layer of about 80 m depth was present. The second will use observations from the central equatorial Pacific in a region with strong surface wind stress and vertical shear, but with weak cooling and strong daytime heating. In this experiment, the mixed layer will be dominated by surface wave and shear-induced turbulence and will extend to only about 20 m depth. The last test will be with data taken off the coast of California that is characterized by weak shear and moderate surface wind stress and heat flux. Here, the mixed layer decays and reforms to about 40 m with a strong diurnal signal. These three cases will be performed to test the basic response of the 2-D model and to determine when the surface layer can be accurately simulated with a 2-D model. The effects of rotation, surface wave action, and bias in the resolved turbulent eddy scales require a 3-D framework. Conversion of the 2-D model to three dimensions will begin after the 2-D tests are completed.

Results to Date. Preliminary results for the three test cases indicate that the model performs well in conditions of weak shear and low surface

stress or when convective mixing is dominant. However, with strong surface stress, the 2-D model fails to generate the proper mixing or an accurate diurnal signal in the velocity profile. Estimation of the turbulent dissipation rate in the mixed layer yields values comparable to the observed dissipation. In the large-vertical-shear case, the model was not able to predict the strong dissipation beneath the mixed layer that was observed. This inability most likely results from a failure of the subgrid-scale model in situations with strong stratification.

CO_2 MEASUREMENTS ALONG THE WOCE P-16 AND P-19 SECTIONS IN THE SOUTH PACIFIC OCEAN: A JOINT LDGO/WHOI PROGRAM

TAKAHASHI, TARO

LAMONT-DOHERTY GEOLOGICAL OBSERVATORY

FY 1991	315
FY 1990	70
FY 1989	0

10/15/90-10/14/91

Objective. To contribute accurate data on the carbon chemistry of seawater to a global oceanic data base for numeric modeling.

Product. Tabulated carbon-chemistry properties of Pacific Ocean seawater and an evaluation of the compatibility of total CO_2 and alkalinity measurements made by different methods.

Approach. Three carbon-chemistry properties will be measured in seawater from the Pacific Ocean along the WOCE P-16 and P-19 lines. Measurements of total CO_2, total alkalinity, and partial pressure of CO_2 from at least one-third of the 440 sampling stations will yield profiles of carbon chemistry with depth in the Pacific Ocean. At least two samples of the surface mixed layer will be analyzed at every station. Aboard ship, total CO_2 will be measured with a coulometer, and total-alkalinity analyses will be performed with an automated potentiometric system. A number of samples will be analyzed for total CO_2 by both the coulometric and manometric methods to resolve disagreement between the methods and to evaluate the compatibility of coulometric and manometric total CO_2 data.

CO_2 partial pressure will be determined aboard ship with an equilibrator/gas-chromatograph system. Some seawater samples will be stored for onshore total-alkalinity determinations by potentiometric acid titration. If possible, the CO_2-chemistry data sets will be produced in a gridded format for numeric modeling. Because virtually no carbon measurements exist for either the surface or deep water of these areas of the Pacific Ocean, the total CO_2, pCO_2, and alkalinity measurements to be made during this project will fill an important data gap.

Results to Date. Because of delays in the refitting of the R/V Knorr, the field work planned for this project was modified. Analytical equipment and personnel for WOCE line P-17 were loaded on the R/V Thomas Washington, which departed from San Diego, Calif., on May 31, 1991. The CO_2 analyses during the first leg were carried out jointly by technicians from WHOI and LDGO with WHOI equipment. During the 40 days of this leg of the expedition, approximately 1500 seawater samples were analyzed for the total-CO_2 concentration and about one-third as many for the alkalinity. Additional samples were collected for land-based manometric analysis of total CO_2 concentration.

The second leg of this expedition, WOCE lines P-17 from 6°S to 32°S and P-16 from about 19°S to 45°S, is currently in progress and will use LDGO equipment for the determination of the total CO_2 concentration and CO_2 partial pressure in seawater samples. Additional samples will be collected for manometric determination of the total CO_2 concentration in seawater.

VERTICAL ARRAYS FOR THE HEARD ISLAND ACOUSTIC FEASIBILITY EXPERIMENT ON MONITORING GLOBAL WARMING

VON DER HEYDT, KEITH

WOODS HOLE OCEANOGRAPHIC INSTITUTION

FY 1991	275
FY 1990	0
FY 1989	0

11/01/90-02/28/92

Objective. To build, deploy, and process the data from two vertical-line arrays for the Heard Island feasibility experiment.

Product. One vertical-line array deployed off the Pacific coast near Monterey and one deployed off Bermuda.

Approach. The Heard Island feasibility experiment for exploiting acoustics to monitor global warming will use high-powered, low-frequency sources to transmit sound in the frequency band of 50 to 67 Hz. Several receiving stations will try to record these signals. These include fixed horizontal arrays and a towed horizontal array. This project will address two serious shortcomings of the suite of receivers by providing for two vertical-line arrays that offer a number of advantages for detecting and analyzing the Heard Island signals. They can be deployed in the sound-channel axis, where the signal levels are higher. High array gains can be obtained. They can generally have low noise levels. And they can resolve the vertical distribution of acoustic energy, which contains useful oceanographic information.

Large-aperture, vertical arrays have many attractive benefits and have been used extensively in many recent experiments concerned with long-range, low-frequency acoustic propagation. Their most important feature is that they provide an estimate of the vertical distribution of the acoustic energy at a receiving site. This distribution is very sensitive to the ocean environment through which the sound propagates, and this property has been exploited for both ocean tomography and matched-field source detection.

The Pacific array will be deployed and operated by MIT, Woods Hole, Monterey Bay Aquarium Research Institute, and the Naval Post Graduate School. The Bermuda array will be deployed and operated by SAIC.

Results to Date. Two vertical arrays were deployed during the Heard Island transmissions. The array off Bermuda was lost because of a failure in the mooring. One attempt has been made to recover it, and a second is scheduled for October. The array off Monterey was successfully deployed, and data was recorded on approximately 20 channels. The signal-to-noise ratio (SNR) was low (-10 dB/Hz on a single channel), as it was for all sites in the Pacific, and was felt to result from bottom interaction near Antarctica and east of New Zealand. Signal processing has increased the SNR to +5 dB in a 15-mHz bandwidth on a single channel. Initial modal decomposition of the array data has been done. The first five modes can represent 75% of the energy. Both frequency and wavenumber spectra suggest the energy in the higher modes to be high. This issue is still a focal point of the analysis. Work continues to examine the modal decomposition and its sensitivity to the number of modes in the representation, time-window duration, SNR, and array tilt.

INORGANIC-CARBON MEASUREMENTS FOR THE WORLD OCEAN CIRCULATION EXPERIMENT - HYDROGRAPHIC PROGRAM

WALLACE, D. W. R., and JOHNSON, K.

BROOKHAVEN NATIONAL LABORATORY

FY 1991	283
FY 1990	312
FY 1989	0

10/01/90-09/30/91

Objective. To collect the comprehensive, intercomparable, high-quality CO_2 data on samples collected during the World Ocean Circulation Experiment Hydrographic Program (WOCE/HP) one-time survey in the Atlantic Ocean that are required for estimating carbon fluxes in the ocean and for understanding the relationship between CO_2 and climate.

Product. Inorganic-carbon and basic biomass data sets in sufficient density to allow calculation of carbon fluxes and storage with water-mass-transport and ocean-circulation models.

Approach. Shipboard analysts on WOCE/HP cruises will analyze almost all water samples for dissolved inorganic carbon (DIC), pH, and pCO_2. DIC will be measured by automated coulometric titration, pCO_2 by headspace catalytic gas chromatography with flame-ionization detection, and pH by a specially designed pH cell interfaced to the coulometric system. These are state-of-the-art methods that have been selected to yield the highest possible precision, accuracy, and processing efficiency for the greatest number of samples at sea. In addition to inorganic CO_2 measurements, the basic biomass parameters (chlorophyll *a*, particulate organic carbon and nitrogen, and depth of the euphotic zone) will be measured during selected cruises. These field measurements will allow carbon cycling to be related to remotely sensed variables, such as chlorophyll.

Results to Date. The first coulometric C_T analyzer was constructed and tested, and we participated in an intercalibration experiment coordinated by Scripps Institution of Oceanography. During a cruise along 19°S (WOCE A9/Meteor 15) aboard the German research vessel FS Meteor, we made >800 C_T analyses, pCO_2 determinations, and exploratory pH measurements. To support these data, we collected quality-control C_T samples for onshore manometric analyses, took alkalinity samples, made daily Secchi-disk readings (to provide estimates of integrated biomass), and measured two novel anthropogenic tracers: F113, and CCl_4. A second cruise to the northern North Atlantic (WOCE A1/Meteor 18) was undertaken in conjunction with CO_2 analysts from the Institut for Meereskunde, Kiel, Germany, with two coulometric analyzers aboard. Analysis of the data collected during these cruises is ongoing.

In addition to field work, five coulometric CO_2-analysis systems have been constructed, tested, and certified for use by groups involved in the Global CO_2 survey. This work involved calibration assurance to accuracies of 1 part in 2000 and necessitated considerable basic research. BNL hosted a 1-week training course for potential recipients of these instruments.

MEASUREMENTS OF SURFACE-OCEAN CO_2 PARTIAL PRESSURE DURING WOCE

WEISS, R. F.

SCRIPPS INSTITUTION OF OCEANOGRAPHY

FY 1991	48
FY 1990	75
FY 1989	0

06/01/91-05/31/92

Objective. To assess the spatial and temporal roles of the oceans in the global carbon cycle with emphasis on the potential for the ocean to absorb fossil-fuel CO_2.

Product. Data tables and plots as well as digital data on pCO_2 and pN_2O in ocean surface water and the atmosphere.

Approach. Shipboard measurements of pCO_2 and pN_2O in surface water and the atmosphere will be made along approximately three WOCE/HP lines per year. The measurements will be made by an automated, high-precision gas chromatographic system that measures CO_2 by flame ionization after quantitative reaction to methane in a stream of hydrogen with a reduced-nickel catalyst preceded by a palladium catalyst. Nitrous oxide will be measured by a separate electron-capture detector. The system will be able to measure CO_2 and N_2O in the ocean and atmosphere about twice per hour.

Results to Date. Unfortunately, progress on this research has been delayed very significantly by delays in the entire U.S. WOCE effort caused by the lack of an acceptable research vessel on which to carry out the program. The R/V Knorr was scheduled to carry out the first U.S. WHP effort in the eastern South Pacific at the end of 1990, and we were to carry out our research on that expedition. The effort is seasonally limited by the weather in the Southern Ocean portions of the work, and it appears that shipyard delays in R/V Knorr's refitting will now cause at least a 2-year delay in these expedition legs

In the meantime, a smaller ship, the R/V Thomas Washington, has been pressed into service for the lower-latitude WHP work in the eastern Pacific, and we have installed our automated chromatographic system on that vessel. We could not, however, send one of our people to sea with the instrument because of severely limited berthing space. Instead, the system is being run by technicians working primarily for other shipboard programs, and we are trying to oversee the effort by ship-to-shore electronic mail.

QUANTITATIVE LINKS

The *sense* of science is that greenhouse gases can theoretically cause warming, but the *state* of science is one of incomplete model prediction and inconsistent observations. Scientists and politicians alike seek verification that the climate is indeed being changed and that the cause is an increase of greenhouse gases. But convincing evidence is evasive, and the lack of certitude about cause, magnitude, and timing of climate change is scientifically unsatisfying.

Unequivocal detection of climate change, including greenhouse warming, is needed. Unambiguous data and scientifically valid approaches do not now exist. The Quantitative Links Program seeks to resolve this problem.

Research Objectives. The objective of the Quantitative Links program is to establish the relationships among and processes controlling (1) changes in atmospheric composition (particularly in CO_2 concentration), (2) changes in radiative fluxes, and/or (3) changes in temperature or other aspects of climate that may result from changes in atmospheric composition. A broad range of research on the linkages between changes in atmospheric composition and global change is conducted. Measurements (field and laboratory) to quantify the relationships are the primary focus.

Improved ability to project future climate will best be achieved by the acquisition, assembly, and analysis of climate data; by the further development, analysis, and verification of climate models; and by observational studies of climatic processes. This capability is a central goal of the Quantitative Links program.

Atmospheric Radiation Measurement (ARM) Program

ARM is a major component of the Quantitative Links Program and is a key component of the Department's research strategy to address global climate change. The ARM Program is a direct continuation of DOE's decade-long effort to improve general-circulation models (GCMs) and to provide reliable simulations of regional and long-term climate change in response to increasing greenhouse gases.

The ARM Program is a highly focused observational and analytical research effort that will compare observations with model calculations in the interest of accelerating improvements in both observational methodology and GCMs. During the ARM Program, DOE will continue to collaborate extensively with existing global-change programs at other agencies.

Research Objectives. The objectives are (1) to quantitatively describe the radiation balance from the surface to the top of the atmosphere and to determine the atmospheric characteristics responsible for this balance, (2) to improve the parameterization of the formation and evolution of clouds in climate models, and (3) to create an experimental testbed for testing process models used in GCMs and for the support of satellite ground-truth measurements.

Research Questions. The research involves a network of ground-based remote-sensing instruments along with campaign studies with aircraft and tethered platforms. Measurements include vertical profiles of temperature, water

vapor, trace gases, and aerosols as well as measurements of solar and infrared radiation. The ARM data will provide the testbed for the process models representing the cloud-climate feedbacks in the present GCMs as well as in the future climate-change-prediction models of regional-scale resolution. ARM focuses on quantitative links between greenhouse gases and climate change and examines climate feedbacks and energy fluxes in the coupled land/atmosphere/ocean system. In addition, the research examines atmospheric cycling and transformation of radiatively and chemically important trace species.

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Research Summaries

MONITORING THE RESPONSE OF THE UPPER TROPOSPHERE/LOWER STRATOSPHERE TO A GREENHOUSE-GAS SCENARIO

COX, STEPHEN K.

COLORADO STATE UNIVERSITY

FY 1991	150
FY 1990	149
FY 1989	0

05/01/91-04/30/92

Objective. To develop a system capable of simultaneously monitoring the increased CO_2 concentrations and signals of global warming by radiometric methods.

Product. Observations necessary for advancing climate models and linking the processes leading from increased greenhouse gases to global climate change.

Approach. The method is based on field measurements of the downwelling radiation field with a moderate resolution interferometer. By examining the relative changes in the zenith-viewed atmospheric radiance over time and the ratios of the radiance at two observation angles, information on the concentration of CO_2 and the resulting changes in CO_2 emission temperatures may be extracted. A more detailed analysis of the data would also provide an estimate of variation in H_2O emission and cirrus cloud cover. Monitoring these three climatic modulators will substantially enhance the ability to establish the linkages of increasing CO_2 concentration to climate change.

Results to Date. Accurate calibration of the moderate-resolution emission interferometer is essential. Two calibration methodologies have been established. The first uses thermoelectrically controlled black-body sources, and the second uses a pool of liquid nitrogen and a copper cavity black-body source. The latter system has been deployed at a mountain site in northern Colorado at an elevation of about three kilometers. The high elevation site was chosen to escape the influence of lower-level moisture and pollutants. Spectra are being collected under various atmospheric conditions at selected observation zenith angles. The spectral collections are supported by radiosonde launches and by background regional monitoring of greenhouse-gas concentrations.

DATA-BASE SUPPORT TO ASSIST IN QUANTIFYING THE LINK BETWEEN CHANGES IN ATMOSPHERIC COMPOSITION AND CLIMATE CHANGE

CUSHMAN, R., and KANCIRUK, P.

OAK RIDGE NATIONAL LABORATORY

FY 1991	511
FY 1990	442
FY 1989	0

10/01/90-09/30/91

Objective. To provide the quality-assured data sets needed for quantifying the relationship between changes in atmospheric composition and changes in climate.

Product. A numeric data package based on a quality-assured long-term climate data set (including monthly surface-air-temperature, precipitation, and atmospheric-pressure values) that is global in spatial extent; numeric data packages based on climate-related data sets that were acquired from the Soviet Union, quality-

assured, and documented; and a priority list from climate researchers of the most important extant climate-related data sets needed for quantifying the link between radiative balance and atmospheric temperature.

Approach. Data from the *World Weather Records* and *Monthly Climate Data for the World* will be supplemented with additional data sets. The expanded data set will be quality-assured, corrected where possible to remove erroneous data, documented, and packaged for distribution as a numeric data package.

Under the auspices of existing United States-USSR bilateral agreements, existing climate-related data sets residing in the Soviet Union will be identified. The most important to the quantification of the link between radiative balance and atmospheric temperature will be acquired. In collaboration with the Carbon Dioxide Information Analysis Center, these data sets will be quality-assured, documented, and packaged for distribution as numeric data packages.

Climate researchers around the world will be surveyed to identify the most important extant climate-related data sets for quantifying the link between radiative balance and atmospheric temperature. A follow-up survey will be conducted to rank the data sets so identified from the standpoint of programmatic needs.

Results to Date. Numeric data package NDP-041 (The Global Historical Climatology Network: Long-Term Climate Data) was compiled in collaboration with the National Climatic Data Center. NDP-041 includes monthly surface-air-temperature, precipitation, and atmospheric-pressure data from the World Weather Records and Monthly Climate Data for the World supplemented with additional data to increase spatial coverage. The data were quality-assured (and corrected where possible) and documented. As a result of contacts and subsequent data exchanges with researchers in the Soviet Union, two additional NDPs were produced by the Carbon Dioxide Information Analysis Center: Atmospheric CO_2 Concentrations Derived from Flask Samples Collected at USSR-Operated Sampling Sites (NDP-033) and Daily Temperature and Precipitation Data for 200 Stations in the USSR (NDP-040). Also, global and hemispheric temperature data received from Soviet researchers were incorporated into CDIAC's *TRENDS '91: A Compendium of Data on Global Change.* A survey of quantitative-links researchers identified additional data sets for CDIAC to pursue as possible NDPs in support of the Quantitative Links Program: data on cloud fraction and type for the globe, aerosol optical depth at the Rattlesnake Mountain Observatory, in-situ and lidar measurements of stratospheric aerosols, and surface sensible and latent heat fluxes.

OBSERVATIONAL ANALYSIS OF CLIMATE FEEDBACKS AND TRENDS

DEL GENIO, ANTHONY D.

GODDARD INSTITUTE FOR SPACE STUDIES

FY 1991	136
FY 1990	133
FY 1989	0

05/01/91-04/30/92

Objective. To reduce the current uncertainty in global climate sensitivity through analysis of observations of currently unconstrained feedback processes and to define useful climate parameters and regions for detecting greenhouse gas-induced climate changes during the nineties.

Product. Techniques that will constrain climate models, reducing uncertainty in linking increasing trace gases to climate change.

Approach. Global observations will be analyzed of three climate feedbacks or forcings that are central to the detection and understanding of

long-term climate change: clouds, water vapor, and ozone. The ISCCP and SAGE I and II data sets will be the primary sources of information on these variables and will be supplemented by available data from SMMR. First, these data sets will be searched for evidence of correlated variations on seasonal or interannual time scales that reveal the sense of climate feedbacks, especially those produced by changes in moist-convection strength or depth. Each of the final data sets will span almost a decade. Long-term trends and correlated patterns of change in the data will then be sought as evidence of an increasing greenhouse effect. Because clouds, water vapor, and ozone all have the potential to affect upper-troposphere or lower-stratosphere temperatures, the research will assess whether any changes observed are consistent with radiosonde evidence of long-term trends in the vertical thermal structure of the atmosphere.

Results to Date. The seasonal variation of SAGE II water-vapor profiles for two years indicates that water vapor in the upper troposphere increases from the cooler to the warmer season at all latitudes. This result is consistent with strong, positive, water-vapor feedback. Analysis of changes in the GISS GCM moisture budget in response to prescribed sea surface temperature changes indicates that water-vapor feedback is positive because increased cumulus subsidence drying in a warmer climate is offset by increasing moistening by cumulus detrainment, mesoscale cumulus updrafts, and the large-scale general circulation.

Analysis of ISCCP cloud optical thickness indicates that, contrary to previous aircraft-data analyses limited to midlatitude continents, low-cloud optical thickness generally decreases with increasing temperature at most latitudes, especially over the oceans. The reflectance of tropical convective anvil cirrus increases with increasing cloud top height when measured locally, but reflectance and height are negatively correlated when temporal variations averaged over the entire tropical west Pacific are considered. This result suggests compensating positive and negative feedbacks in adjacent regions as sea surface temperature rises.

ICRCCM PHASE II: VERIFICATION AND CALIBRATION OF RADIATION CODES IN CLIMATE MODELS

ELLINGSON, ROBERT G.

UNIVERSITY OF MARYLAND

FY 1991	468
FY 1990	373
FY 1989	0

05/01/91-04/30/92

Objective. To carry out a comprehensive program of measurement and analysis to establish an absolute standard against which to compare models.

Product. More-accurate radiation models for use in parameterizing climate models.

Approach. A comprehensive program of measurement and analysis, called SPECTRE (Spectral Radiance Experiment), will be carried out to establish an absolute standard against which to compare models and to remove the hidden variables (unknown humidities, aerosols, etc.) that have lent uncertainty to radiation models. This program will employ two surface spectrometer teams and the radio acoustic sounding system for temperature profiling to produce a set of accurate atmospheric spectral radiation data measured simultaneously with the important radiative properties of the atmosphere. Many other instruments, such as lidars, will also be used to contribute to the understanding and modeling of not only trace-gas greenhouse effects but also the cirrus greenhouse effect.

The major unfinished ICRCCM goal is evaluation of the ability of the radiation codes used in climate models to simulate the real atmosphere. Another round of model intercom-

parisons will be held to pursue this goal; however, this time the models will be compared with SPECTRE observations and with each other.

Results to Date. Activity has centered on the sensitivity analyses of radiation model calculations and on the acquisition and testing of instrumentation prior to the field measurement program in November 1991. Our radiation-model calculations show that the maximum random error in spectral radiance is about 1.5% per Kelvin temperature error and about 0.8% per percent relative humidity error. The effects of systematic errors are larger than random errors by about a factor of 2. Nevertheless, the results show that the errors in the calculations should be kept below about 8% in the regions of relatively strong lines and about 5% in weakly absorbing regions with the type of observational errors we expect to encounter. Such small errors should allow much more stringent tests of the parameterizations of the water-vapor continuum than heretofore possible.

The emission spectrometers to be used in the experiment have been procured and are now under testing along with the various computer programs necessary to process interferograms to spectra. The tests to date indicate the spectra can be measured in the 500 to 1500 cm^{-1} region with an accuracy of the order of 0.5% full scale.

THERMOHALINE CIRCULATIONS AND GLOBAL CLIMATE CHANGE

HANSON, HOWARD P.

UNIVERSITY OF COLORADO AT BOULDER

FY 1991	162
FY 1990	134
FY 1989	0

07/15/91-07/14/92

Objective. To investigate the sensitivity of the thermohaline circulation of the North Atlantic to the changes in surface forcing that may be expected with CO_2-induced global warming.

Product. An understanding of the role in global warming of a potentially important feedback between the rate of CO_2 uptake by the ocean and the production of cold water in the North Atlantic.

Approach. The approach will begin with simple sensitivity studies to address the role of hydrological forcing vs thermal forcing in the model. The role of mesoscale eddies in the annual cycle of mixed-layer deepening and retreat will be investigated. Salinity, topography, and realistic coastlines will be explicitly included in the calculations. The feedback process can then be addressed, and the climate sensitivity to the feedback will be assessed from the model.

The numerical experiment will tackle the important problem of ocean-climate interactions. It will be a good complement to ongoing eddy-resolving calculations of circulation in the North Atlantic being made for the World Ocean Circulation (WOCE) that may provide new insight about high-latitude ocean circulation lacking in coarse-grid ocean GCMs.

This research will improve the quantitative understanding of the long-term changes in global temperature that may be expected to occur with increasing concentrations of CO_2 in the atmosphere and will improve estimates of the ocean's ability to dissolve CO_2. Because the research involves the behavior of the ocean on time scales of decades, no existing data sets are appropriate for developing this understanding, and the future data collection efforts are unlikely to be sufficiently timely to provide the needed information. Numerical modeling is, therefore, required.

Results to Date. Because hydrologic forcing associated with spring runoff is an important factor in deep-water formation, the timing and amount of the freshwater input to the North Atlantic from the Great Lakes and St. Lawrence

system is of interest. A study of the spring departure of ice from the Great Lakes was completed, and a secular trend toward earlier ice departure was found. This result correlates with a tendency for an earlier spring runoff maximum through the St. Lawrence. Because this freshwater input to the North Atlantic is a factor in stabilizing the water column against vertical mixing, it appears that small changes in climate over the past 30 years may already be having an influence on the oceanic circulation.

The importance of this result is amplified by the sensitivity of the springtime mixed layer of the North Atlantic to small changes in surface forcing. The model used in this project has exhibited a very sensitive behavior to small changes in surface heating; initially, this was thought to be a numeric artifact. However, recently published observational results suggest that this sensitivity may be real. Consequently, a new effort is being undertaken to examine where the surface forcing will be most effective in stimulating this sensitive behavior.

CLOUD AND OCEAN EFFECTS ON GREENHOUSE WARMING

HOFFERT, MARTIN I.

NEW YORK UNIVERSITY

FY 1991	217
FY 1990	212
FY 1989	0

07/15/91-07/14/92

Objective. To investigate effects of global cloudiness variations on global climate and their implications for cloud feedback and to continue development and application of NYU transient climate/ocean models with an emphasis on coupled effects of greenhouse warming and feedbacks by both the clouds and oceans.

Product. A quantitative assessment of how transient climate change may be hidden by cloud feedbacks and by ocean thermal delay.

Approach. Cloud, surface temperature, and ocean data sets, as interpreted by a focused climate/ocean model, will be used to develop a cloud-radiative-forcing scenario for the past 100 years; to assess the transient climate response; to narrow key uncertainties in the system; and to identify those aspects of the climate system most likely to be affected by greenhouse warming over short, medium, and long time scales. Apart from short-term transients on the decadal time scale, the research approach will aim at better understanding of "latent" climatic effects (i.e., global climatic and environmental changes to which our planet may be effectively committed, but which are temporarily "hidden" as a result of thermal storage by the oceans).

The effects of cloud radiative forcing on global climate response will be assessed with an extension of the methodology previously employed to assess solar variability effects on climate. Used in this manner, the simplified model will assist in developing an understanding of the key processes before investigating with the GCMs.

Results to Date. Our NYU ocean/climate model has been further developed and expanded for this study. A new 1-D transient ocean version has been developed that includes feedback from density stratification on vertical mixing and interactive calculation of upwelling as a function of depth. Spin-up calculations show that the model gives an excellent representation of Levitus steady-state world ocean vertical density and temperature profiles. Recalculation of transient global climate responses to the IPCC scenarios are in progress. Also, a 2-D (latitude-depth) ocean version is running at LLNL to explore latitude-by-latitude transient climate response and to develop methods for comparing transient atmosphere/ocean climate models in general.

Major uncertainties in transient climate response come from uncertainties in equilibrium-GCM climate sensitivities arising from different

parameterizations of clouds and cloud radiative feedback. Our approach to climate sensitivity bypasses the GCM route by reconstructing both the forcing and response of selected paleoclimates. We estimate empirically and independently a planetary cooling rate of 2.2 W/m^2-^oC ± 10%, in the middle range of IPCC sensitivities. Should this value withstand subsequent paleo-testing, it could be used to project more-confident transient global warming rates for the next century.

LINKAGE OF ANTHROPOGENIC AEROSOL TO CLOUDS AND CLIMATE

HUDSON, JAMES G.

DESERT RESEARCH INSTITUTE

FY 1991	135
FY 1990	125
FY 1989	0

07/15/91-07/14/92

Objective. To quantitatively establish the definition of cloud condensation nuclei (CCN).

Product. A basis for separating the relative effects on cloud microphysics of natural and anthropogenetic CCN and definitions of the nucleus supersaturation range appropriate to stratus clouds and of the relative efficiency of nuclei to active cloud formation.

Approach. The definition of cloud condensation nuclei will be established. This definition will distinguish between the overall roles of natural and manmade nuclei in cloud formation. Such a distinction will allow a determination of the linkage between global air pollution and cloud microphysics that would enable realistic estimates to be made of this possible anthropogenic effect on cloud radiation balance and climate.

A measurement program for CCN, based on proven techniques, will be carried out. Cloud formation, radiative properties, and precipitation characteristics depend on the number, size, and chemical properties of the CCN. This effort will collect data on the size and number. The CCN will be measured with the instantaneous CCN spectrometer previously developed and proven. The device provides a detailed CCN spectrum over the entire range of interest to cloud physics, and the nuclei actually active in cloud formation can be subtracted from the total aerosol.

Identification of the CCN can then lead to determination of the cloud-activation efficiency over a given size range and other radiative properties of the CCN.

Surface and aircraft measurements will be used to collect CCN/aerosol samples for analysis. Wet and dry aerosols will be separated electrostatically, and the direct chemical as well as water-solubility properties of the materials will be determined.

Results to Date. The high-temperature processor and data-acquisition system have been completed. Laboratory measurements with the high-temperature processor show that it provides extremely sensitive measurements of particle volatility. Shipboard measurements in project SEAHUNT confirmed that most of the maritime CCN are not NaCl but behave as ammonium sulfate.

In the presence or vicinity of drizzle under the California stratus deck, the concentration of CCN usually decreased. This appears to be caused by "coalescence scavenging." These measurements indicate the importance of particle-removal processes in the CCN budget.

This process was in evidence on July 13 when especially clean air was encountered; concentrations were less than 2 cm^{-3}. During this episode, a very distinct aerosol plume was encountered (150 cm^{-3} about 7 miles in width) that was apparently the result of ship emissions. Surface measurements of solar energy associated this

observation with passage under a cloud line that may have been a ship trail. This unusually clean air caused by drizzle may be a precondition for ship-trail formation. The large numbers of nuclei from the ship may stabilize the cloud by inhibiting the coalescence process. Various ship plumes were measured, and the apparent production rate of these ships ($\sim 10^{16}$ s^{-1}) was sufficient to produce ship trails.

NETWORK-BASED SOLAR AND METEOROLOGICAL CHARACTERIZATION OF CLOUD-RADIATION EFFECTS IN GLOBAL CLIMATE MODELING

LAULAINEN, N., and MICHALSKY, J.

PACIFIC NORTHWEST LABORATORY
and STATE UNIVERSITY OF NEW YORK AT ALBANY

FY 1991	254
FY 1990	100
FY 1989	0

10/01/90-09/30/91

Objective. To investigate how clouds interact with longwave (infrared) and shortwave (solar) radiation to regulate the heating of the planet.

Product. An understanding of how the atmosphere, especially clouds, force the "top-of-the-atmosphere" infrared and solar radiation to observed values; whether cirrus clouds are increasing in the nonovercast sky condition; and whether the tropospheric aerosol burden is changing with time and how it affects a cloudy-sky albedo.

Approach. Clouds mask about half the earth's surface at any given time. Thus, it is important to know how clouds interact with outgoing longwave (infrared) and incoming shortwave (solar) radiation to regulate the heating of the planet. Moreover, it is important to understand how these processes vary with time, with cloud type, with cloud structure, and with geography. To investigate these effects, a nine-station regional network will be established in the eastern United States. Each station will be equipped with standard instruments for measuring ambient temperature, total precipitation, and relative humidity. Observations of diffuse horizontal, total horizontal, and direct normal solar irradiance will be made with a multidetector rotating shadowband radiometer (MDRSR) in six narrow wavelength bands and one broad band. All three solar radiation components will be measured for each wavelength band with the same sensor for increased stability. Upward-looking horizontal infrared and local surface albedo will supplement these instruments and will aid in the interpretation of their results. Of greater utility, perhaps, than the solar observations themselves will be the climate-sensitive parameters derived from them: cloudiness, cloud optical depth, cloud type (to some extent), and aerosol optical depth and its wavelength dependence. This approach will allow us to use our ground-based measurements in concert with satellite results to characterize cloud radiative forcing for a variety of cloud types and structures over a limited geographical area, to track changes in cirrus frequency and optical depth, and to track changes in aerosol optical depth and its wavelength dependence.

Results to Date. The design, construction, and testing of the MDRSRs have been completed. This activity includes work on the optical detector assembly, its associated signal-conditioning electronics, the detector housing, the shadowband assembly, the data-acquisition unit, and the associated electronics.

Nine candidate sites in the northeastern United States have been selected for this project, and installation of the MDRSRs and associated instruments has been completed. Software to perform the automatic interrogation of the data loggers, downloading of data to the host computer system, and its subsequent processing has been completed.

SIGNAL AND NOISE IN GLOBAL-WARMING DETECTION

NORTH, GERALD R.

TEXAS A & M UNIVERSITY

FY 1991	98
FY 1990	96
FY 1989	0

07/15/91-07/14/92

Objective. To estimate the length of climatological record required to identify a global-warming signal over natural variability.

Product. An understanding of the adequacy of the historical instrument record to resolve the issue of signal and noise in global warming.

Approach. The current debate as to whether or not the climate has changed and, if so, what the cause might be hinges on the historical data set. If the record is not sufficient over the period of observation to resolve natural variability (i.e., to distinguish between signal and noise), then the possibility of a quantitative link is slim.

The present research will increase understanding of the global trend-observing system by conducting a statistical analysis of the variability and resolving those trends into their natural and random sampling components. Idealized mathematical models, such as noise-forced energy balance models and GCM runs of idealized planets, will be used to produce long-time-series data for analysis. This approach will provide the information needed to assess how long a data set may be required to determine natural variability. Although "real" data will not be used, the approach seeks understanding before more-complicated climate models are applied to the task.

A formalism recently devised by North and Nakamoto will be used for sampling-error analysis. The technique can be applied to physical fields exhibiting random fluctuations over a space-time spectrum. For this research the technique will be applied to the space-time spectrum of the surface-temperature field.

Results to Date. Experiments have been performed with the NCAR GCM to gain a better understanding of the fluctuations in the surface temperature field. Quantifying the statistical structure in space-time is important in evaluating errors in estimation of the global average temperature by a finite set of point gages. Three papers are in press that report that

- Simple stochastic models are good imitators of GCM output so far as the surface temperature is concerned
- The response of the surface temperature field to externally imposed perturbations is linear
- The stochastic climate model made plausible by the studies above was used to calculate the variance and spatial autocorrelation statistics for the real world with land-sea geography and to compare the geographical distribution with the same fields taken from a 40-year data set, giving an agreement that is quite good and suggesting that we have found a tool that can be used in the signal and noise analysis of the measurement system applied to planet Earth

MODIFICATION OF CLOUD OPTICAL PROPERTIES BY AEROSOLS

NOVAKOV, TIHOMIR

LAWRENCE BERKELEY LABORATORY

FY 1991	316
FY 1990	309
FY 1989	0

10/01/90-09/30/91

Objective. To quantify the links between the optical properties of clouds and those of

atmospheric aerosols, such as sulfates and carbonaceous particles.

Product. A laboratory and field data set to estimate the optical properties of aerosols and clouds.

Approach. A combination of field and laboratory experiments will be conducted to determine how the optical properties of clouds respond to changing concentrations of anthropogenic, biogenic, and natural aerosols. To assess the importance of aerosol-cloud interactions, horizontal, vertical, and seasonal variations in global concentrations must be known. This task will rely on the compilation, evaluation, and analysis of existing ambient and source-emissions data.

The radiative properties of natural clouds will be measured to determine the validity of theoretical predictions of increasing cloud albedo with increasing CCN (particularly sulfate and mineral dust) concentrations. The relative impacts of energy-related, crustal, and biogenic aerosols on radiative properties of clouds will be determined. The soot content of natural cloud drops will be determined so the possible role of soot particles in decreasing cloud albedo can be assessed. Results obtained from these field studies will be used to design laboratory experiments with the LBL cloud chamber to identify the physics and chemistry of dominant importance in modifying the optical properties of clouds, with special emphasis on enhanced-absorption, soot-associated clouds. Finally, the compilation and analysis of ambient and source emissions data pertaining particularly to soot aerosols will be compliled and analyzed to obtain horizontal, vertical, and seasonal variations in global aerosol concentration.

Results to Date. A backscattering nephelometer for in-cloud use was constructed and theoretically described. Directly measured cloud backscattering coefficient (i.e., the albedo of a unit thickness cloud) compares favorably with Mie-theory calculations based on separately measured cloud drop size and number concentration.

Cloud backscattering coefficient measurements have been measured in conjunction with total and interstitial aerosol concentrations (and chemical composition) and cloud drop size and concentration during two field campaigns on El Yunque Peak in Puerto Rico. The data obtained cover a wide range of meteorological and transport conditions resulting in aerosol concentrations differing by more than two orders of magnitude.

A global black carbon (BC) emission inventory has been constructed with a method that assumes that ambient BC and SO_2 are highly correlated in source-dominated environments worldwide. The global BC emissions are obtained by multiplying empirically derived characteristic BC/SO_2 ratios by more accurately known SO_2 emissions. This inventory is used as an input to a global BC modeling study at LLNL.

THE ROLE OF AEROSOLS AND CLOUD MICROPHYSICS IN CLIMATE AND CLIMATE CHANGE

PENNER, JOYCE E.

LAWRENCE LIVERMORE NATIONAL LABORATORY

FY 1991	292
FY 1990	100
FY 1989	0

10/01/90-09/30/91

Objective. To use data analysis together with a global model to quantify the effects of aerosols and clouds on the radiative budget of the earth and climate.

Product. Quantification of the link among aerosols, cloud microphysical properties, and climate.

Approach. Available data will be compared with the predictions of a 3-D global model for aerosols and clouds. Data on individual sulfur species, aerosol concentrations, elemental carbon concentrations, and cloud microphysical properties will be used. The results from the global model will primarily be compared with long time series of data for single stations or with satellite data, but comparison with more short-term episodic data will also provide valuable insight and allow even short-term data to be folded into the analysis. In this way, the data from a single station or even an event will be able to be extrapolated to determine the global impact.

Results to Date. A review of published scavenging ratios for trace species (HNO_3, soot or black carbon, $SO_4^=$, and SO_2) have led to a significant revision of the model's precipitation-scavenging scheme. The revised model gives improved results for HNO_3 deposition. The results for sulfate are currently being analyzed. A global black carbon inventory has also been developed. Initial results of model simulations with sulfur and black carbon indicate that sufficient amounts of black carbon are present in aerosols to significantly decrease their scattering potential and their potential for cooling the climate. The impact of sulfur aerosols on cloud albedos remains high. The estimated increase in reflected solar radiation from biomass burning and sulfate aerosols is 2 Wm^{-2} and 4 Wm^{-2}, respectively.

OCEAN-CLOUD/CLIMATE LINKAGE STUDY

PORCH, WILLIAM M.

LOS ALAMOS NATIONAL LABORATORY

FY 1991	297
FY 1990	260
FY 1989	0

10/01/90-09/30/91

Objective. To improve the understanding of how marine stratocumulus clouds respond to changes in atmospheric composition and atmospheric warming and thus feed back on climate.

Product. Improved ocean-cloud parameterizations in climate models and ocean data stratification for satellite cloud-trend studies.

Approach. The effect of heating and aerosol nucleation on marine stratocumulus clouds will be determined by studying the effect of ships on cloud development and albedo. Experiments will be conducted under meteorological conditions favorable to ship-trail development in ocean regions where clouds are particularly sensitive to anthropogenic influence. Ships with the potential for ship-trail formation will be followed by research vessels uniquely equipped to probe and sample the trails. The results will be used to test and improve dynamic and aerosol microphysics-based numeric cloud models. The results from the experiments and model studies will be used to provide a matrix of sea surface temperature and marine-boundary-layer conditions occurring during high-resolution-image satellite overpasses of these cloud-sensitive regions, aiding in the interpretation and development of trend analysis of cloud fraction, albedo, and atmospheric composition.

Results to Date. The SEAHUNT (Ship-Trail Evolution above High-Updraft Naval Targets) experiment was conducted in July in the Northeastern Pacific Ocean. It was the first measurement of aerosol and meteorological parameters associated with a ship-trail cloud. We sought and located meteorological conditions that were so favorable to ship-trail formation that we were able to produce a ship-trail cloud from our own small ship. On the same expedition we were able to make the first measurements of the response of the marine boundary layer to a total solar eclipse. In addition, we made extensive measurements of the effect of a tropical storm on the subtropical marine boundary layer, the diurnal cycle of boundary-layer cloud properties, and the

variation of marine aerosol and meteorological properties as functions of the distance from the coast. Preliminary analysis of the data from the just-completed experiment show the importance of drizzle in the reduction of cloud condensation nuclei (CCN) and the importance of low CCN concentrations and a shallow marine boundary layer in ship-trail cloud formation. The results of this experiment will be used to improve numeric models of marine stratocumulus and ship-trail cloud development. A numeric model developed at LANL that has been applied to a stationary heat source effect on marine clouds has been improved to model a moving source and will be applied to better understand the observations made during SEAHUNT.

CLOUD-ALBEDO PERTURBATIONS ON CLIMATE

SCHWARTZ, STEPHEN E.

BROOKHAVEN NATIONAL LABORATORY

FY 1991	579
FY 1990	100
FY 1989	0

10/01/90-09/30/91

Objective. To search for evidence, principally in satellite data, for the enhancement of cloud albedo by anthropogenic SO_2 emissions and to systematically evaluate the magnitude, as a function of time and location, of the perturbation in cloud albedo caused by anthropogenic SO_2 in the context of other sources of cloud condensation nuclei (CCN), principally biogenic sulfur compounds.

Product. Information allowing critical testing of hypotheses linking responses of the earth climate to changes in radiative forcing.

Approach. A definitive assessment of enhancement of the cloud albedo by anthropogenic sulfate aerosol and a quantitative evaluation of that enhancement will be carried out. The long-time-average (e.g., annual) enhancement in planetary albedo from this mechanism will be mapped. Historical (100 year) trends will be evaluated with historical emissions patterns derived from records of fuel use and fuel sulfur content.

Enhancement of the albedo of low-altitude marine stratus clouds caused by anthropogenic SO_2 emissions and/or biogenic DMS emissions will be systematically searched for in the ERBE data. A spatially resolved inventory of gaseous sulfur emissions will be prepared for use in global evaluations of the anthropogenic perturbation of cloud albedo. An initial spatially resolved assessment of present and historical anthropogenic enhancement of cloud albedo will be prepared that incorporates into GCM calculations a linear or other simple, assumed relation between CCN concentration and modeled $SO_4^=$ concentration.

Available data will be systematically analyzed to prepare an improved relation between sulfate aerosol concentration and CCN concentration. The possibility of using satellite measurements of aerosol optical density as a surrogate for modeled sulfate will be evaluated.

Results to Date. Significant correlation has been found between the albedo of low-altitude marine stratus clouds (from satellite data from the Earth Radiation Budget Experiment) and biological productivity (from chlorophyll concentrations from the Coastal Zone Color Scanner) for the North Atlantic. These results suggest an influence of biogenic emissions on cloud albedo.

The fractional incorporation of aerosol particles into cloud droplets in stratus and stratocumulus clouds was examined by comparing the number concentration of cloud droplets (2 to 20 μm in diameter) with the total number concentration N of cloud droplets plus interstitial aerosol particles (0.2 to 2 μm). Fractional incorporation is near unity at low N (less than 600 per cm^3) but decreases with increasing N. Although a fall-

off in incorporation decreases the sensitivity of cloud radiative forcing to anthropogenic aerosol particles, the onset of the phenomenon is at such high N that remote marine atmospheres still have great sensitivity.

Considerable progress has been made in assembling the components necessary to model anthropogenic sulfate for the 1986 time frame (emissions, winds, and other meteorological fields) and in acquiring and processing satellite data to permit examination of albedo as a function of modeled sulfate concentrations.

MECHANISMS CONTROLLING THE PRODUCTION AND TRANSPORT OF METHANE, CARBON DIOXIDE, AND DISSOLVED SOLUTES WITHIN A LARGE BOREAL PEAT BASIN

SIEGEL, DONALD I.

SYRACUSE UNIVERSITY

FY 1991	154
FY 1990	207
FY 1989	0

07/15/91-07/14/92

Objective. To determine the degree to which solute and gas movement in deep organic soils is controlled by local ground-water flow systems and their associated vegetation community types and by regional subsurface hydrogeologic settings.

Product. A definition of the potential release of CO_2 and methane from boreal peat basins.

Approach. Little is known about the dynamics and potential feedbacks of peatlands, an important carbon storage reservoir. They are sensitive to changethat has the potential to significantly alter the carbon-storage-release balance.

An integrated modeling and field study of solute transport and ground-water flow conditions in the Glacial Lake Agassiz peatlands of northern Minnesota will be used to investigate the rates of carbon accumulation and loss and the fluxes of methane and CO_2; the physical and botanical factors controlling the production of methane and CO_2 within the peat profiles; and the role of hydrogeological processes in controlling the fluxes of gases solutes through the peat.

Measurements will be made of hydraulic-head gradients and solute and gas concentrations in the major vegetation communities of the peatland. The fluxes of dissolved solutes and gases from the peat in each vegetation setting will be determine from these data by mathematical modeling of the advection-dispersion equation, tested by isotopic mass balances on carbon. The results from these detailed site-specific studies will be integrated into the larger peatland setting by relating the variations in solute fluxes to the proportions of each major vegetation type in the larger peatland.

The chemical portion of this study will rely on microsampling of gases and solutes obtained throughout the depth profile of the peat. Standard methodologies will be applied.

Isotopic analysis ($\Delta^{13}C$) will be used to provide evidence for the processes by which methane is produced and transformed within the peat.

Results to Date. During a severe drought in August 1990, hydraulic-head measurements were made, and samples of peat-pore water and dissolved gases were obtained throughout 33 peat profiles in bogs and fens of the extensive Glacial Lake Agassiz peatlands. At every bog, the hydraulic head increased with depth throughout the peat profile, indicating that the bogs occur over groundwater-discharge areas, whereas groundwater mostly moved horizontally in fens. Concentrations of dissolved solutes in the pore water confirmed that ground water was advecting upward into the bog peat. These observations are completely unexpected and contrary to two commonly held views that raised

bogs are divorced from groundwater and that they are groundwater recharge areas where ground water moves downward. A second unexpected result was the pattern of dissolved methane in the peat columns. At depths of about 1 m below the water table, practically all pore water was supersaturated with methane. With further drought, this methane pool will be intersected by the lowering water table, likely providing elevated carbon fluxes to the atmosphere.

Subsequent to the 1990 summer field season, the drought broke in northern Minnesota. Preliminary results of our resampling of many of the sites in August 1991 suggest that, although the bogs no longer are discharge areas, methane concentrations still remain high in pore water in the peat. This most recent field work was made in collaboration with researchers from Florida State University and the National Center for Atmospheric Research, who measured surface fluxes from the peat to the atmosphere. Future synthesis and comparison of the data sets from 1990 and 1991 will provide important information on how methane and carbon dioxide emissions might change with drier conditions in the upper midwest predicted by some of the global climate models.

THE EFFECT OF CLOUD MICROPHYSICS ON CLIMATE SENSITIVITY

STAMNES, KNUT

UNIVERSITY OF ALASKA

FY 1991	77
FY 1990	74
FY 1989	0

07/15/91-07/14/92

Objective. To develop cloud radiative parameterizations based on liquid-water content and cloud-drop-size distribution for use in a radiative-convective model to assess the impact of potential greenhouse-warming changes in cloud microphysics on cloud/radiation feedback and thereby climate sensitivity.

Product. A more realistic treatment of clouds in climate models through methods based on cloud microphysics.

Approach. The cloud liquid-water content and drop-size distribution will be used to define cloud radiative properties. Reliable and efficient parameterization of scattering and absorption/emission by cloud droplets will be developed, providing a better understanding of the role of cloud microphysics in the determination of cloud radiative properties. A radiation model including these cloud parameterizations will be used to investigate seasonal and latitudinal effects of the influence of cloud microphysics and liquid-water content.

A detailed, 1-D radiative-convective model will be used to study the role of cloud microphysics in the determination of cloud radiative properties. This radiative-convective model will be used to obtain first estimates of the surface-temperature response to potential changes in cloud microphysics associated with greenhouse warming. It will also be used to assess how cloud droplet size influences cloud/radiation feedback and thereby climate sensitivity. The climatic implications of changes in cloud microphysics in 1-D and multi-dimensional climate models will be assessed.

Results to Date. An accurate parameterization for the radiative properties of water clouds has been developed. Based on Mie theory, calculations for cloud-droplet-equivalent radii in the range of 2.5 to 60 microns reveal that cloud optical properties depend primarily on equivalent radius throughout the solar and terrestrial spectrum and are insensitive to the details of the droplet size distribution, such as shape, skewness, and modality, as well as total number concentration. This result suggests that in cloud models it suffices to determine the second and third moments of the size

distribution that defines the equivalent radius. It also implies that measurements of the cloud liquid-water content and extinction coefficient are sufficient to determine cloud optical properties experimentally. Based on the detailed calculations, the optical properties are parameterized as a function of cloud liquid-water path and equivalent radius with a nonlinear least-squares fitting. Comparison of cloud warming and cooling rates computed from this parameterization with similar results obtained from exact Mie calculations shows that our parameterization yields very accurate results and that it is several thousand times faster. This parameterization separates the dependence of cloud optical properties on droplet size and liquid-water content and is suitable for inclusion into climate models.

DETERMINING THE CHEMICAL COMPOSITION OF CLOUD CONDENSATION NUCLEI

WILLIAMS, ALLEN L.

ILLINOIS STATE WATER SURVEY

FY 1991	462
FY 1990	430
FY 1989	0

07/15/91-07/14/92

Objective. To develop the instrumentation and methodology to determine the chemistry of cloud condensation nuclei (CCN) in ambient air samples.

Product. Data for the characterization of CCN values and cloud microphysics in GCM models.

Approach. The underlying CCN spectrum determines, to a large extent, the cloud-droplet spectra and influences the resulting cloud radiation properties. As a result, an understanding of the CCN chemistry is critical to realistic analysis of the role of clouds in climate-warming scenarios.

The appropriate instrumentation and methods to determine the CCN chemistry in ambient air samples will be developed. Air will be continuously drawn into a flow-type thermal-diffusion cloud chamber to form droplets on the CCN at precisely controlled supersaturations. The droplets will be removed immediately from the flow stream to minimize contamination. The droplets will then be collected on a filter for analysis. Microgram amounts of CCN material should be able to be collected and subjected to chemical analysis by liquid ion chromatography and atomic adsorption.

Other techniques would be investigated including x-ray fluorescence, neutron activation, mass spectroscopy, and electron microscopy. The ability to analyze smaller amounts of material, yet obtain a sufficiently wide range of target compounds, is important for the routine use of the instrumentation.

Results to Date. The current phase of the project involves the design, construction, and testing of the different components of the flow system: a 4- x 12-ft continuous-flow diffusion chamber, a 4- x 12-ft haze chamber with nine plates wetted on both sides, and three virtual impactors that operate at a flow of 1300 L/min. A numeric model is being developed to calculate the CCN mass that would be collected under different operating conditions with special attention focused on the supersaturations encountered as the CCN pass through the system and on the effect of nonideal impactor size cutoffs.

CCN active at above 0.1% supersaturation will be collected separately for chemical analysis in addition to the more massive but less numerous CCN of smaller than 0.5 μm dry diameter that are active below 0.1% supersaturation. Microgram amounts of CCN material are expected to be collected from an hour of sampling.

The first complete system is nearly constructed. Upon its completion, testing and ambient

sampling will begin. The second system, which is to be placed on a portable platform, is in earlier states of construction and is expected to be operational early in 1992.

TECHNICAL REVIEW OF CARBON DIOXIDE RESEARCH INITIATIVE PROPOSALS

WOHLPART, A.

OAK RIDGE ASSOCIATED UNIVERSITIES

FY 1991	349
FY 1990	221
FY 1989	0

10/01/90-09/30/91

Objective. To provide the technical review of proposals submitted in response to the Carbon Dioxide Research Initiatives and to conduct technical meetings in support of program objectives.

Product. Statistical data and reports that will assist DOE in assuring the quality of the review process and in making funding decisions.

Approach. Program documents will be provided to potential applicants upon request, proposals will be received and administratively screened, a proposal data base and software to manage the program will be developed, review meetings will be coordinated, the comments and recommendations of review panels will be documented, and other assistance will be provided as required. Technical support for scientific meetings, including meeting logistics and proceedings, will be provided.

Results to Date. Technical assistance was provided to identify experts, convene review panels, and otherwise facilitate the evaluation of proposals submitted in response to requests for proposals in several specified areas of CO_2 research.

STATISTICAL EXAMINATION OF CLIMATOLOGICAL DATA RELEVANT TO GLOBAL TEMPERATURE VARIATIONS

WOODWARD, W.; GRAY, H.; and GUNST, R.

SOUTHERN METHODIST UNIVERSITY

FY 1991	188
FY 1990	184
FY 1989	0

07/15/91-07/14/92

Objective. To construct a state-of-the-art statistical model of global temperatures.

Product. A better understanding of the variables and the changes in the variables associated with the predicted CO_2-induced climate change.

Approach. Models for measures of mean global temperature change will be developed with state-of-the-art statistical techniques, appropriate new methodology, and a variety of data bases consisting of relevant explanatory variables. Attention will be given to the integrity of existing data, as well as to the definition and measurement of global temperature change. The hypothesis of a recent warming trend will be tested with the interest being whether such a trend, if it exists, is forecast to continue. The impact on warming of changes in the explanatory variables will be investigated, and the contributions of each of the explanatory variables to the cycles, trends, and random variations in the warming/cooling process will be ascertained. Data sources will not only include recent records, but will also include biological and chemical data collected from archeological and geological studies.

A statistical model relating global temperature to a collection of exploratory variables will be constructed. Development and use of appropriate transfer-function models, including the

possibility of long-memory processes, will be a major thrust of the research.

Results to Date. The global-temperature-change series of Hansen and Lebedeff and of Jones et al. were modeled with a variety of time-series techniques, specifically fitting ARMA models and models with a deterministic trend superposed on a stationary process. All tests found a significant trend in the two temperature series, and thus the resulting fitted models forecast the trend to continue. However, ARMA models fit to these series do not forecast a trend to continue. Simulation studies show that the tests for trend have a high false-alarm rate for various types of stationary processes, including ARMA models fit to the temperature series.

With a well-accepted definition of a spatial mean, we investigated estimates of mean global temperature change using uniform (unweighted), distance-weighted, and statistically robust averages. We showed, theoretically and from computer simulations, that unweighted averages are superior to distance-weighted averages for estimating a spatial mean over a region, that robust averages are superior to unweighted and distance-weighted averages when outliers are present among the temperature anomalies, and that gridding is beneficial when station locations are unevenly spaced throughout a region. These results have been used to obtain a new temperature-change series from the 1990 NCAR data.

USE OF A LASER-BASED MONITORING TECHNIQUE TO MEASURE TRACE-GAS FLUXES ACROSS THE AIR-SEA INTERFACE

ZIKA, ROD G., and MILNE, PETER J.

UNIVERSITY OF MIAMI

FY 1991	138
FY 1990	145
FY 1989	0

07/15/91-07/14/92

Objective. To implement a sensitive spectroscopic technique that is photothermally based and that is based on measuring the in situ weak infrared absorption features of carbon gases and to initially assess its use in two areas of air-sea gas transfer.

Product. An improved measurement strategy and quantification of the fluxes of trace and carbon gases at the atmosphere-ocean interface.

Approach. For many trace gases of interest (e.g., CO_2, CO, CH_4, and nonmethane hydrocarbons), both the magnitude and even the sign of the air-sea concentration difference, which is the term that drives the gas flux across the air-sea interface, is poorly known. A larger number of observations need to be made to provide reliable, globally averaged values for these terms, and a measurement technique needs to be developed to overcome the technical limitations associated with these measurements.

A sensitive, photothermally based spectroscopic technique will be developed for measuring the in situ weak IR absorption of atmospheric carbon gases. Photothermal deflection spectroscopy (PDS) has the potential of being both a very sensitive and fast-responding gas sensor. Its capabilities will be assessed by using it to measure the abiotic photochemical production of atmospheric trace gases in the surface ocean and to measure the photoperiod control of biologically respired trace gases in the surface ocean.

Results to Date. The PDS technique has been developed and refined in a number of ways. Computational aids for the efficient identification and selection of IR absorption bands of target gases have been implemented. They are largely based on the HITRAN database and they include programs to allow the calculation of spectral lineshapes and bandwidths under given conditions of atmospheric composition, pressure, and temperature. The stability of a red laser diode as a probe beam in the PDS technique has been examined as a

replacement for the lockable single-frequency HeNe lasers that conventionally have been used. A sensitive position-sensing device based on a duo-lateral silicon photodiode has been constructed; its associated circuitry and control electronics include the use of a lock-in amplifier as a signal processor for detection of the modulated probe beam.

In regard to the end-use applications, a high-temperature-oxidation total-organic-carbon (TOC) procedure has been implemented to quantify dissolved organic carbon in seawater, and investigation of a hydrocarbon (so far only tentatively identified by GC-MS) emitted by several phytoplankton cultures has commenced.

ARM Initiative

Research Summaries

INTEGRATED CLOUD OBSERVATION AND MODELING

ACKERMAN, THOMAS P.

PENNSYLVANIA STATE UNIVERSITY

FY 1991	665
FY 1990	637
FY 1989	0

09/15/91-09/14/92

Objective. To use available observation systems to study cloud formation, cloud properties, and radiation transfer in the atmosphere; to develop data-assimilation models; and to use explicit simulations of small-scale cloud processes for the purpose of developing suitable parameterizations for large-scale atmospheric numeric models.

Product. Information on methods of observation and data assimilation that are suitable for testbed sites of the ARM program and parameterizations of cloud processes for large-scale atmospheric models.

Approach. With the suite of instruments used in the Pennsylvania State University's Cloud Observing System (COS), data will be collected for several extended observing periods and analyzed for such quantities as vertical velocity, cloud cover, cloud optical properties, and surface radiation budgets. With these observations, the vertical structure of the atmosphere that is equivalent to the structure simulated at an individual grid point of a mesoscale numeric model or a general-circulation model (GCM) will described. Methods for 4-D data assimilation will be developed to provide data inputs efficiently to atmospheric models.

Methods will be developed and applied to exchange data between fields produced by a mesoscale model with modules that describe the atmospheric boundary layer (lower 2 km of the atmosphere) and detailed cloud processes. Interactions of processes on small scales and the mesoscale will be examined carefully and parameterized as needed for large-scale models. As part of this work, radiative-transfer models to simulate the interactions between microphysical and radiative processes will be applied and compared to the measurements of cloud and radiation properties. As better understanding is achieved, improved parameterizations of cloud processes will be incorporated into available mesoscale models and tested.

Results to Date. The COS was operated as an integrated system from January to May of 1991. Although the operation was less reliable than anticipated, considerable experience and several excellent data sets were acquired. With this experience and data, a variety of data-analysis techniques for the COS are being developed and/or improved. Several case studies of stratus and cirrus formation and evaluation are being carried out with data acquired by the COS. A detailed 1-D cloud microphysical model is undergoing active development. The current model incorporates all the relevant liquid-water processes and is being used in the study of stratus formation. Also, the development of a nonhydrostatic version of the Penn State/NCAR mesoscale model has been completed.

REMOTE SENSING OF SURFACE FLUXES IMPORTANT TO CLOUD DEVELOPMENT

BARNES, F.; CLEMENTS, W. E.; and PORCH, W.

LOS ALAMOS NATIONAL LABORATORY and UNIVERSITY OF ILLINOIS

FY 1991	300
FY 1990	0
FY 1989	0

11/01/90-09/30/91

Objective. To determine the scaling relationships of upward fluxes of water vapor and heat from the surface and their interconnections to variabilities in surface features and parameters important to cloud-formation processes.

Product. Characterization of the convective and mixing processes over a range of scales and surfaces and subsequent delineation of the influence of these processes on the local radiation budget and cloud processes.

Approach. An integrated measurement program will be developed to study the patterns of surface fluxes of water vapor and heat for sites under a range of surface and meteorological conditions. These measurements will be used to evaluate the appropriate measurement scale of the upward fluxes as they relate to cloud processes and radiation transport. The 3-D structure of the lower atmosphere will be detailed, and observed patterns in the atmosphere will be correlated with both surface vegetation and terrain pattern and inhomogeneities recorded in the cloud layer at an established CART site.

The spatial and temporal variabilities in heat and water-vapor flux rates will be determined and related to variations in the radiative balance above the site. With the help of collaborators, the time-dependent vertical distribution of water vapor from the surface to the cloud layer will be mapped.

Remote-sensing technology (e.g., lidar-ceilometers) will be used to monitor cloud cover; these data will be related to cloud cover determined by satellite imagery and/or multispectral digital imaging. The topographic and terrain features will be established with digital maps, and standard ecological features will be measured. Surface albedo measurements will be obtained from aircraft-mounted instruments or remotely controlled platforms.

The scaling characteristics of the evaporative fluxes will be examined over a variety of ranges up to the subgrid scale of mesoscale models and the grid size of GCM models. The flux fields over a CART site will be correlated with cloud characteristics and dynamics over and downwind from the site. The feedbacks between the surface and the atmosphere that contribute to cloud formation over or downwind from a site will be evaluated with modeling studies.

Results to Date. In collaboration with researchers from PNL, ANL, NOAA/ATDD, and other institutions, we conducted a field campaign in Boardman, Oregon, from May 28 to June 25, 1991. The site was an extensive area of

semiarid rangeland bordered by farmland consisting of 50-ha central-pivot irrigated fields. The overall goals were to arrive at appropriate techniques for averaging heat and moisture fluxes from point and localized measurements to successively broader scales, finally representing a larger domain of about 100 km^2.

We deployed 13 micrometeorological flux stations in three experiments. The first evaluated interinstrument comparability; the second evaluated fine-scale variability in moisture fluxes over a small area (approximately 2 ha) in the desert grassland; and the third determined spatial averages for different domains throughout the area with instruments deployed in locally homogeneous plant communities (including both irrigated crops and semiarid-rangeland plant communities). In a fourth experiment, a triangular array of optical cross-wind sensors was deployed in the desert to study the relationship between point and spatially averaged measurements of heat flux and convergence. Vegetative cover on dominant plant species was measured along transects in the rangeland and within the irrigated fields. Soil-moisture measurements (gravimetric and with time-domain reflectometry) were performed periodically at both agricultural and rangeland sites. Ground and meteorological data will be used in conjunction with aircraft, meteorological, and ground measurements obtained by PNL, ANL, and NOAA/ATDD collaborators to assess the relationships between surface heterogeneity and variability in surface fluxes at different scales.

PHOTOMETRIC STUDIES OF CLOUDS FROM AN ARM SITE

BUCHWALD, MELVIN

LOS ALAMOS NATIONAL LABORATORY

FY 1991	180
FY 1990	0
FY 1989	0

11/01/90-09/30/91

Objective. To monitor cloud covers and their radiation-transfer properties over an ARM site to improve understanding of the role of clouds in the Earth's radiation budget.

Product. An inexpensive, autonomous cloud-measurement system that can obtain the data necessary to test theoretical cloud models.

Approach. The project will develop and field an all-sky photometer based on a fully-computer-controlled, intensified CCD digital camera system with sufficient resolution and dynamic range to operate both day and night. Two such systems would be used to acquire simultaneous observations from different positions to provide stereoscopic cloud data (viz., distance, size, and height). The initial system will be developed and tested. The system will be deployed at an ARM site. A dedicated system will be constructed, including the theoretical work necessary to determine a wide range of additional cloud parameters. A second dedicated system will be constructed. And the data-analysis procedures for the resulting hardware will be developed and demonstrated.

Results to Date. An instrument composed of a filter wheel and a scientific CCD camera has been built to explore the utility of spectral imaging for sky-brightness measurement. It allows the collection of images with a dynamic range of 14 bits per pixel. The instrument was carried to Boardman, Oregon, for the ARM surface-flux experiment to explore measurement of water vapor. A filter transmission of 950-nm is strongly absorbed by water compared to 900-nm transmission, but both passbands exhibit similar scattering. When 950-nm images were divided pixel-by-pixel by 900-nm images, missing image brightness caused by water-vapor absorption became apparent. A promising use of this imaging technique is as a complement to horizontal imaging for aerosol measurement. These images are now being analyzed, and procedures are being considered to use information gathered by this new technique. Nighttime images with the two filters were also

collected. Clear nighttime sky allows the stars and moon to be used for the measurement of column water-vapor densities. The 950- to 900-nm ratio in each pixel is nearly the same as the water-vapor extinction. Use of images in this spectral region, sensitive to the most important greenhouse gas, should be a valuable complement to cloud detection and analysis.

SCIENCE TEAM PARTICIPATION IN THE ARM PROGRAM

CESS, ROBERT D.

STATE UNIVERSITY OF NEW YORK
AT STONY BROOK

FY 1991	52
FY 1990	50
FY 1989	0

09/15/91-09/14/92

Objective. To act as an interface between the ARM program and several related NASA projects involving satellite measurements and a NOAA project wherein ground-based and satellite measurements are compared.

Product. Ehanced coordination between the ARM program and related NASA and NOAA projects.

Approach. ARM Science Team Meetings will be attended, knowledge gained in other related programs will be shared, and ways of interfacing with these programs will be suggested.

Results to Date. Primary effort has been devoted to a prototype ARM study to investigate the shortwave radiative impact of clouds on the atmospheric column. The specific intent was to demonstrate what could be achieved by collocating shortwave radiation measurements made from an RPV with similar near-surface measurements. This prototype study used near-surface net downward shortwave-radiation measurements made at the Boulder Atmospheric Observatory Tower. The surrogate for an RPV was the GOES geostationary satellite. Because the GOES shortwave scanner is neither a calibrated nor a broadband instrument, combined calibration and unfiltering was performed with collocated ERBE pixels.

This combined data set demonstrated that the shortwave radiative impact of clouds on the atmospheric column was typically that of heating in the morning and cooling in the afternoon. This is physically consistent with low stratus clouds in the morning causing enhanced upward-reflected radiation and hence enhanced shortwave absorption by the atmospheric column. In contrast, afternoon cirrus tend to shadow the underlying atmosphere.

RADIATIVE-TRANSFER-MODEL DEVELOPMENT IN SUPPORT OF THE ARM PROGRAM

CLOUGH, S.

ATMOSPHERIC AND ENVIRONMENTAL
RESEARCH, INC.

FY 1991	213
FY 1990	209
FY 1989	0

09/15/91-09/14/92

Objective. To provide a highly accurate radiative-transport model for scattering and nonscattering atmospheres; to use calculations from this model for parameterizations in GCM radiative-transport codes; to validate this code against experimental measurements and high-accuracy model predictions; and to support the design, analysis, and interpretation of the CART measurement program.

Product. Improved radiative-transport parameterizations for general-circulation models.

Approach. In the effort to develop a high-accuracy model, FASCOD3 will be implemented

as a research-grade reference radiative-transfer model for GCM-related calculations. Improved algorithms and interrelated data will be developed and supported for FASCOD3 to improve the accuracy of radiative-transfer calculations in both the short- and long-wavelength regions. Develop An updated water-vapor-continuum model will be developed and the algorithms necessary for updating the continuum as a result of new measurements and/or modified water vapor for far-wing line shapes will be maintained. Technical support will be provided for the maintenance of spectroscopic databases (i.e., the GL HITRAN line-parameters database, a transition spectral database, and realistic scattering properties of clouds and aerosols) for the ARM program.

For the development of the rapid model, the necessary algorithms and technical support will be provided for the calculation of the parameters required for the development of radiative-transfer models appropriate to GCM calculations. The calculation of statistical and correlated *k* distributions, transmission functions, and high-accuracy radiative-transfer calculations for rapid radiative-transfer-model validations will be addressed. The two-stream rapid radiative-transfer algorithm of Toon et al. will be studied and validated with particular emphasis on the spectral overlap problem for different molecular species. The improvement attainable from using four streams with a rapid diagonalization procedure will be studied, and the computational expense will be established.

Technical support will be provided in recommending measurements to address requirements for radiative-transfer-model improvements for GCMs. Support will be provided for the analysis and interpretation of measurement results, and the results will be incorporated into the models and databases as appropriate. Radiative-transfer calculations will be performed with the high-accuracy model in both the short- and long-wave region for specific measurement situations chosen by the ARM Scientific Team. Calculations will be performed with the rapid radiative-transfer model on extended measurement sets to validate and improve the model. A close collaboration will be maintained with researchers involved in spectral radiance and transmittance measurements, and particular emphasis will be placed on spectral cloud properties and on molecular-spectroscopic issues, including continuum and heavy-molecule effects.

Results to Date. The initial version of a code for the accelerated computation of radiative transfer for scattering media has been completed and is in the testing phase. This code is being developed to provide a line-by-line radiative-transfer model for the analysis of spectral data from the longwave and shortwave spectrometers at the ARM sites. Current timing results indicate that calculations for a 500-cm^{-1} spectral interval, three layers, and a sampling interval appropriate to the upper tropopause will take 30 seconds for 32 streams on a CRAY-YMP and 0.5 seconds for 4 streams and will provide a computational accuracy of the order of 0.1%. The code is also intended to serve as a reference model for the development of rapid radiative-transfer algorithms. The required input for the scattering medium for the current code is the spectrally dependent single-scatter albedo and the moments of the phase function. The code is based on the doubling-adding method and takes advantage of the slow spectral dependence of the scattering parameters.

As a direct consequence of this research on the multiple-scattering code, significant computational enhancements (by a factor of 20) for vector computers have been obtained for line-by-line calculations of radiances and fluxes for the clear atmosphere.

PARAMETERIZATION OF CONVECTIVE CLOUDS, MESOSCALE CONVECTIVE SYSTEMS, AND CONVECTIVELY GENERATED CLOUDS

COTTON, WILLIAM B.

COLORADO STATE UNIVERSITY

FY 1991	192
FY 1990	271
FY 1989	0

09/15/91-09/14/92

Objective. To use a mesoscale cloud model to develop cloud parameterizations for use in GCMs.

Product. A physical understanding and numeric techniques adequate to develop algorithms in GCMs that characterize heat-exchange (radiative, latent, and sensible), optical, and other properties of clouds accurately and with computational efficiency.

Approach. A highly capable and documented model will be used to develop cumulus parameterization schemes that include contributions of both deep and shallow convection and of mesoscale vertical velocities; to identify criteria that determine if ordinary cumulonimbus or mesoscale convective complexes will dominate for a given set of conditions; to examine the feasibility of simulating cirrus clouds created from the outflow of cumulus clouds; and to test the parameterization schemes with data, including ARM data.

Results to Date. The cumulus parameterization scheme was constructed in two dimensions and compared to an explicit simulation of Florida sea-breeze convection. Although the scheme had some shortcomings, the general approach seems to be viable. The scheme is currently being extended to the third dimension to allow for the development of parameterizations of mesoscale convective systems (MCS).

To verify the cumulus parameterization scheme, a quasi-3-D (or channel) simulation was run with convective-scale processes explicitly calculated. Our test case (deep convection along Florida sea-breeze fronts) agreed well with observations and with our 2-D explicit simulations.

Results of the explicit fine-grid (1.5-km) scale run are being averaged to the grid scale of the cumulus parameterization runs (4.5-km and 20-km) to give a quantitative measure of how well the parameterization scheme performs.

For the extension of our approach to parameterizing mesoscale convective systems, we have begun simulations of the June 3-4, 1985, MCS that occurred during the PRESTORM project. Once a 3-D simulation of the case has been satisfactorily verified, we will begin performing conditional sampling analysis to create a data base for extending the parameterization scheme. We are also in the process of selecting a tropical MCS case for simulation and analysis.

AREA-REPRESENTATIVE ESTIMATES OF SURFACE HEAT FLUX FOR CART SITES

COULTER, RICHARD L.

ARGONNE NATIONAL LABORATORY

FY 1991	200
FY 1990	0
FY 1989	0

11/01/90-09/30/91

Objective. To develop methods for integrating local and nearly local heat-flux estimates made at CART sites to produce an overall estimate representative of the extended CART-site areas.

Product. Transfer functions for estimating representative surface heat-flux values for extended CART areas from direct local measurements of surface heat flux and visualizations of larger-scale meteorological features.

Approach. Local-surface heat-flux estimates at many sites within the extended CART domain will be used in combination with area-averaging techniques (such as sodar and light scintillation) to determine how different categories of surfaces contribute to heat fluxes. These large-scale estimates will be used to estimate still-larger-scale surface heat fluxes that might be inferred from other ARM investigations. Visualization techniques will be used with surface-based remote sensing (lidar, radar, and aircraft) to determine the variability across the CART domain caused by large-scale structures characteristic of the PBL as a whole.

Results to Date. The ARM Cooperative Experiment (ACE) that took place near Boardman, Oregon, from June 4 to June 24, 1990, was used to obtain areally averaged heat fluxes across interfaces between different surface types, namely desert and irrigated crops. The primary contrast was in the moisture content of the surfaces. This created a corresponding contrast in the sensible heat flux. We obtained areally averaged heat-flux estimates over desert, young corn, and mature potatoes with sodar and laser anemometers. Eddy-correlation point measurements were made just upwind of irrigated corn. Other participants in the project will contribute additional eddy-correlation measurements and aircraft flux measurements over the desert-irrigated field complex. Although the weather conditions were less than ideal for the study, a valuable data set was acquired from which preliminary scaling transfer functions can be produced.

DEVELOPMENT OF AN INTEGRATED DATA-ASSIMILATION/SOUNDING SYSTEM IN SUPPORT OF THE DOE ARM EXPERIMENTAL PROGRAM

DABBERDT, WALTER F.

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

FY 1991	594
FY 1990	578
FY 1989	0

09/15/91-09/14/92

Objective. To develop an integrated sounding system (ISS) and data-assimilation system (DAS) to couple in-situ and remote-sensing instruments with a state-of-the-art mesoscale model for data assimilation to provide a time-continuous description of the 3-D atmospheric structure with a resolution of at least 20 km over a domain of 200 x 200 km.

Product. A prototype ISS and mesoscale model adapted to DAS application.

Approach. An existing suite of observational tools (including in-situ networks, remote-sensing systems, and mobile observation capabilities) will be adapted to obtain continuous vertical profiles and some 3-D patterns of wind, temperature, moisture, and important trace gases with ground-based remote sensing (radar, lidar, and radiometry). A state-of-the-art mesoscale dynamical model will be used to assimilate and interpret the data output from the measurement system.

Results to Date. A comprehensive measurement program was conducted during February and March 1991 that yielded high-quality data sets for seven intensive-observing periods. The measurements were conducted in northeast Colorado in conjunction with the Winter Icing and Storm Program (WISP-91). An ISS facsimile was established at Platteville, Colorado, and

included three Doppler UHF/VHF wind profilers with RASS, a Doppler sodar, three microwave radiometers, a high-resolution IR interferometer-spectrometer, a laser-beam ceilometer, nine PAM-II surface stations, and the ASTER surface flux facility. These data are being edited for quality control and assembled into a data archive that will be available to the research community.

The modeling and data-assimilation work to date has focused on development of a nonhydrostatic version of the NCAR/Penn State mesoscale model; development of a 1-D column model for use at individual ISS sites and for sensitivity tests in conjunction with single-column GCM studies; and initial data-assimilation studies with both the hydrostatic and nonhydrostatic model with highly resolved measurements from the WISP-90 and WISP-91 programs.

RADIATIVE PROPERTIES OF NONUNIFORM CLOUDS

DAUM, P. H.; KLEINMAN, L. I.; and STEPHENS, G. L.

BROOKHAVEN NATIONAL LABORATORY and COLORADO STATE UNIVERSITY

FY 1991	240
FY 1990	0
FY 1989	0

11/01/90-09/30/91

Objective. To improve the treatment of cloud-radiation interactions and feedbacks in general-circulation models (GCMs) by focusing on the problem of radiative transfer through clouds in the atmosphere.

Product. New and better predictions of cloud radiative transfer in a way that can be directly incorporated into general-circulation models (GCMs) and related models.

Approach. This program will combine both theoretical and observational studies of radiative transfer to test current parameterizations of cloud radiative-transfer processes; to assess the effects of cloud inhomogeneities on domain-averaged radiative properties; to evaluate methods of retrieval of cloud-droplet-size distributions and liquid-water path from spectral-reflectance measurements; to perform radiative-transfer calculations for clouds with nonhomogeneous microphysical and geometric properties; and to develop new methods of modeling radiative transfer through the atmosphere with broken cloudiness.

MODELING RADIATION, CLOUDS, AND CONVECTION

DICKERSON, MARVIN H.

LAWRENCE LIVERMORE NATIONAL LABORATORY

FY 1991	139
FY 1990	400
FY 1989	0

10/01/90-09/30/91

Objective. To help provide an important theoretical and technical-support component for the ARM study to meet its objective of providing general-circulation models (GCMs) with better atmospheric radiation and cloud parameterizations.

Product. Model parameterizations verified against the ARM observational data sets.

Approach. The measurement design will be refined to meet modeling needs, and the consistency of initial ARM radiative-flux measurements will be checked against theoretical calculations. Scientific management support will be provided to ARM through coordination of modeling studies and participation on the ARM management team. New cloud and radiation parameterizations for models of various time and

space scales will be coordinated and developed. Numeric modeling studies and ARM observational data will be used to develop techniques for evaluating new GCM parameterizations. And numeric modeling studies and ARM data will be used to better define the role of cumulus convection in the vertical redistribution of momentum, sensible and latent heat, moisture, and pollutants on the global scale.

Results to Date. Contributions were made to the overall ARM program planning and execution through participation on the ARM management team and as leader of the Modeling Team. The first ARM Science Team meeting was planned and participated in as were the activities associated with the development of general measurement strategies that help link the Science Team experiments with the observational data base. As part of this development process, several workshops were organized and conducted to determine the Science Team measurement requirements.

Progress was also made in refocusing our cumulus-cloud-modeling research and development from verification studies with smoke from controlled burns of forests to studies involving deep cumulus convection in the western tropical pacific. Plans are being formed to investigate the thermodynamic regulation of ocean warming by cirrus clouds.

POINT-AREA RELATIONSHIPS FOR GLOBAL CLIMATE MODELING

DORAN, J. CHRISTOPHER

PACIFIC NORTHWEST LABORATORY

FY 1991	420
FY 1990	0
FY 1989	0

11/01/90-09/30/91

Objective. To develop procedures for extrapolating local measurements of radiation and heat flux to larger areas representative of a GCM grid cell.

Product. Improved parameterizations of surface heat fluxes for use in GCMs and related models that account for subgrid-scale variability arising from inhomogeneous surface properties.

Approach. Initially, the program will seek to work at a carefully selected site or sites under well-defined, relatively stationary meteorological conditions and over surfaces that will emphasize the importance of subgrid-scale variations in fluxes to test preliminary approaches, identify and correct problems, and analyze initial findings. As part of this effort, interpolation-extrapolation methods will be developed to derive areal average flux values from point measurements; surface and aircraft data will be collected simultaneously, and formulations for GCM grid-sized areas will be examined and improved; mesoscale numeric models will be used as a tool for systematic testing of the effects of surface inhomogeneities. Subsequently, the development of methods that are more general in scope and applicability will be undertaken. These methods will then be applied to specific CART sites.

Results to Date. A field program to measure the distribution of surface fluxes of heat and moisture in a region of sharply contrasting surface characteristics was designed, coordinated, and carried out. A site near Boardman, Oregon, was chosen that featured semiarid rangeland surrounded by irrigated farmland. Seven ground stations were deployed to measure sensible and latent heat fluxes; more than 90 hours of turbulence data were obtained from an instrumented light aircraft; a Doppler sodar was operated to measure winds and mixing-layer heights; and more than 30 profile measurements were made of winds, temperature, and moisture with tethered balloons. The data show substantial differences in the structure of the boundary layer and in the fluxes over the drier and wetter surfaces; sensible-heat peaks in the drier areas were up to four times higher than

the peaks over the irrigated regions, while latent-heat values in the drier areas were as little as one-eighth those over the wetter areas.

LONGWAVE-RADIATION CODES FOR CLIMATE STUDIES: VALIDATION WITH ARM OBSERVATIONS AND TESTS IN GENERAL-CIRCULATION MODELS

ELLINGSON, R., and BAER, F.

UNIVERSITY OF MARYLAND

FY 1991	289
FY 1990	250
FY 1989	0

09/15/91-09/14/92

Objective. To develop an optimum longwave-radiation model for use in general-circulation models (GCMs) that has been calibrated with state-of-the-art observations; to assess the impact of the longwave-radiative forcing in a GCM; to determine the sensitivity of a GCM to the radiative model implemented in the GCM; and to determine how the longwave radiative forcing contributes in comparison with shortwave radiative forcing, sensible heating, thermal advection, and expansion.

Product. An improved longwave-radiative-transport model suitable for implementation in GCMs.

Approach. This program will address a major problem connected with one of the dominant radiation components of the climate problem, longwave radiation. An optimum longwave-radiation model will be developed for use in GCMs that has been calibrated with state-of-the-art observations. The impact of the longwave radiative forcing in a GCM will be assessed. The sensitivity of a GCM to the radiative model used in it will be determined. The contribution of the longwave radiative forcing will be determined in comparison with shortwave radiative forcing, sensible heating, and thermal advection and expansion.

The technical approach toward developing the radiation model will be to test existing models in an iterative, predictive fashion. This project will supply the Clouds and Radiation Testbed (CART) with a set of models to be compared with operationally observed data. The observed differences will lead to the development of new and improved models to be tested with new experimental data. Similarly, the GCM studies will use existing GCMs to study the radiation-sensitivity issues. The anticipated benefits of this approach are a better longwave-radiative-forcing algorithm and a better understanding of how longwave radiative forcing influences the equilibrium climate of the atmosphere.

Results to Date. Different climate-model radiation codes have been obtained, and the level of accuracy at which we will be able to test the models given the measurement uncertainties in the radiometric quantities and the atmospheric radiative properties has been determined. We are about to begin testing ten longwave radiation models with data from the Community Climate Model. Sensitivity analysis of our spectral-radiation model has shown that atmospheric temperatures and water-vapor relative humidities must be measured in the lowest 3 km to within 1 K and 5%, respectively, if we are to be able to distinguish between current models of the water-vapor continuum under clear-sky, low-aerosol conditions. Furthermore, the longwave calculations in the 10-μm atmospheric window shows a large sensitivity to aerosol loading. We are pursuing these results further to see how accurately the aerosol optical properties must be specified to narrow our confidence intervals for radiation calculations.

HIGH-SPECTRAL-RESOLUTION LIDAR TECHNOLOGY FOR THE DOE ARM PROGRAM

ELORANTA, EDWIN

UNIVERSITY OF WISCONSIN

FY 1991	190
FY 1990	204
FY 1989	0

09/15/91-09/14/92

Objective. To develop a lidar that provides high spectral resolution in the backscattered signal and distinguishes between aerosol and air backscatter by their different spectral signatures.

Product. A field-functional high-spectral-resolution lidar and measurements of ice/liquid ratios, particle size, and backscatter profiles in clouds.

Approach. A laboratory-demonstrated instrument system will be adapted to field operation by acquiring, insulating, and wiring a trailer and adding a beam-steering capability, shock mounting hardware, and ruggedized electronics. Development modifications will also be added, including a multiple-scattering capability for studying cloud-particle size and depolarization for ice-crystal/cloud-liquid-water ratios.

Results to Date. No results reported.

TEMPORARY ASSIGNMENT TO THE COMMITTEE ON EARTH AND ENVIRONMENTAL SCIENCES

ELWOOD, J. W.

OAK RIDGE NATIONAL LABORATORY

FY 1991	158
FY 1990	0
FY 1989	0

10/01/90-09/30/91

Objective. To provide staff support to the Committee on Earth and Environmental Sciences (CEES).

Product. Support of the activities of the CEES.

Approach. Anticipated tasks include: (1) reviewing federal research and development programs, including both national and international, in earth sciences dealing with global environmental changes; (2) assisting in the interagency and intergovernmental planning and coordination of R&D programs in earth sciences; (3) identifying and defining R&D needs related to earth sciences; (4) assisting in the preparation of long-range research-planning and budget-planning documents for the overall federal R&D effort in earth sciences; and (5) providing reviews, analyses, advice, and recommendations to the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET) concerning federal R&D policies and programs in earth sciences related to assessing humanity's impact on the global environment.

DEVELOPMENT OF AN INTEGRATED SOUNDING SYSTEM FOR THE ARM PROGRAM

GAGE, K., and WESTWATER, E. R.

WAVE PROPAGATION LABORATORY/NOAA/ERL

FY 1991	134
FY 1990	0
FY 1989	0

10/01/91-09/30/92

Objective. To develop a transportable, integrated suite of existing, state-of-the-art, in situ, and remote (active and passive) sensors to measure all important thermodynamic and kinematic variables (plus some radiative variables) through the troposphere with special attention to high-resolution measurements through the planetary boundary layer.

Product. A design for an integrated sounding system that will include a multifrequency UHF/VHF Doppler wind profiler and RASS; a microwave radiometer; a high-resolution interferometer sounder (HIS); a high-resolution NAVAID atmospheric sounding system; and a surface meteorological station that measures state variables, winds, trace gases, and all components of the surface energy balance.

Approach. An Integrated Sounding System (ISS) will be developed that will consist of a suite of active and passive remote sensors and in situ surface and upper-air systems to provide continuous height-resolved profiles of atmospheric thermodynamic and kinematic variables. The measurements from a network of ISS facilities will be coupled with a state-of-the-art, 4-D mesoscale data-assimilation system, which will provide the ARM Program with a time-continuous description of 3-D, atmospheric structure with horizontal resolution of 20 km or less over a 200- x 200-km GCM grid-scale domain.

A prototype ISS from existing instrumentation at NOAA and NCAR will be tested and then deployed and evaluated in a pilot field program. The results of the pilot field program will guide the ultimate design of the ISS. The design completed, several systems will be produced.

EFFECT OF CLOUDINESS HETEROGENEITY ON THE RADIATIVE BUDGET AT THE TOP OF THE ATMOSPHERE AND AT THE SURFACE: MODELING, VERIFICATION, AND ANALYSIS

GAUTIER, CATHERINE

UNIVERSITY OF CALIFORNIA AT SANTA BARBARA

FY 1991	169
FY 1990	185
FY 1989	0

09/15/91-09/14/92

Objective. To develop new, more-realistic methods of modeling the structure of clouds and improved parameterizations of radiative transfer in cloudy skies.

Product. Basic insights on radiative transfer in clouds and potentially improved descriptions of the behavior of clouds and radiative transfer as simulated by GCMs.

Approach. Innovative methods will be developed to describe the structure and optical properties of cloud fields. Cloud scaling characteristics will be determined from the analysis of satellite data. The basic multifractal parameters will be estimated. New, high-performance computer algorithms will be investigated for more-efficient extraction of the basic multifractal parameters from observations. Then clouds with realistic scaling characteristics will be simulated with multifractal analysis and other methods. Anisotropy will be introduced to simulate the vertical stratification and texture variations of clouds. Different sampling and averaging strategies will be evaluated by modeling the temporal evolution of cloud and radiation fields.

Innovative methods will be developed to describe radiative transfer in cloud fields. Mean radiances and radiation fluxes of clouds will be computed as a function of their scaling characteristics. Approaches will vary from simplified methods to Monte Carlo computations. Departures from plane-parallel theory (used in GCMs) as a function of cloud parameters will be evaluated. Then modeled radiances and fluxes of clouds will be evaluated by comparison to ARM testbed data, observations from satellites, and data collected by complementary programs. The results of the investigations will be applied to improve GCM simulations of clouds and radiative transfer.

Results to Date. Multifractal techniques have been developed and are being used to capture the strong nonlinear variability of cloud and radiative fields as they pertain to TOA and surface radiation budget.

Two new multifractal techniques have been devised and applied to visible and IR satellite data to characterize the scaling properties of the satellite radiance probability distributions (determined by the parameter α) and the scaling anisotropy of cloud-radiance fields. Preliminary results indicate that cloud-radiance fields are not Gaussian (i.e., $\alpha = 2$) because α takes values of 1.8 and 1.4, respectively. These results must be confirmed by analysis of LANDSAT TM and GOES satellite data currently under way. Furthermore, the analysis of these satellite data, which scan a range of scales from 1 to 2000 km, confirms the anisotropic scaling nature of the radiances over the entire range.

A huge amount of numeric experiments based on radiative-transfer computation in 2- and 3-D multifractal clouds (180 CPUs on a Cray-2 have been allocated to this effort) are also presently under way.

Observations of the effect of broken clouds on surface solar irradiance have been interpreted satisfactorily by assuming that the clouds are not Lambertian. With this assumption, the excess flux when the sun is not obscured by the clouds, which varies with the sun zenith angle, and the residual diffuse flux (constant with time) when the sun is obscured are quantitatively explained for reasonable values of cloud optical thickness.

TECHNICAL ASSISTANCE TO DOE/OHER HEADQUARTERS

HALES, JEREMY M.

PACIFIC NORTHWEST LABORATORY

FY 1991	119
FY 1990	90
FY 1989	0

10/01/90-09/30/91

Objective. To provide technical and administrative assistance, through a detailee assignment, to DOE and the Office of Health and Environmental Research.

Product. Planning, monitoring, and guidance of programs within OHER.

Approach. The detailee will spend up to one-third of his time residing in Washington, D.C., interacting with Headquarters staff and representatives of other government agencies. In general, this effort will be addressed to the preparation of reports and associated planning documents related to major DOE/OHER program and initiatives, including ARM, CHAMMP, NAPAP, the Atmospheric Chemistry Program, and the Mesoscale Meteorology initiative.

Results to Date. No results reported.

A JASON STUDY OF ENERGY PROBLEMS — 1991

HENDERSON, ROGERT G.

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

FY 1991	75
FY 1990	75
FY 1989	0

07/15/91-07/14/92

Objective. To bring new scientific expertise, understanding, insights, and critical faculties to the problems faced by the government.

Product. Briefing to the Director of the Atmospheric and Climate Research Division, DOE, and other DOE managers on study results and methods.

Approach. JASON will review the technical progress being made on the Atmospheric Radiation Measurement (ARM) Program, and the Computer Hardware, Advanced Mathematics and Model Physics (CHAMMP) Program. To

provide a comprehensive review of these programs, scientists outside of JASON will be used in addition to selected members of the JASON group.

Results to Date. No results reported.

ARM PROGRAM SUPPORT

HULSTROM, ROLAND L.

SOLAR ENERGY RESEARCH INSTITUTE

FY 1991	49
FY 1990	50
FY 1989	0

10/01/90-09/30/91

Objective. To help conduct technical planning and experimentation for the Radiation Measurements portion of the ARM Program.

Product. A candidate list of radiometric instruments for deployment in the first phase of occupation of the first ARM site, including complete instrument descriptions, a recommendation of essential instruments, options for meeting specific measurement requirements, suggested calibration protocols, and recommended instruments beyond the basic complement.

Approach. SERI will work with the ARM Program and Instrument Team to ensure that the ARM radiation measurements and instrumentation allow the ARM mission to be completed. This effort will include investigations of calibration methods and analyses of total measurement uncertainty for each candidate radiometric instrument. Recommendations will be made for instrument development where available instruments are incapable of meeting ARM requirements (i.e., where total measurement uncertainty is too high or unknown).

Results to Date. We participated in discussions of the basic measurement program, minimum accuracy requirements, and measurement uncertainty techniques for the World Meteorological Organization's Baseline Surface Radiation Network (BSRN) and at the 7th International Pyrheliometer Comparison and the first and second workshops on implementation of the BSRN. We developed, presented, and had adopted (for the BSRN) a method entitled "Measurement Uncertainty Techniques Applied to the BSRN."

We defined an ARM traceability path and estimated its total measurement uncertainty; we also formed an initial reference group of absolute-cavity radiometers to support ARM short-wave broadband solar-radiation measurements traceable to the World Radiometric Reference (WRR).

With NOAA, we compared and characterized short- and longwave radiometers identified for the first ARM CART site.

DATA-MANAGEMENT SUPPORT FOR THE DOE ARM PROGRAM

KANCIRUK, PAUL

OAK RIDGE NATIONAL LABORATORY

FY 1991	175
FY 1990	220
FY 1989	0

10/01/90-09/30/91

Objective. To develop a data-management system to gather, quality assure, analyze, archive, and distribute the vast amount of information produced by the ARM Program.

Product. A well designed research-data-management system for the ARM Program.

Approach. The data-management component of the ARM project will be coordinated and

directed, and data-management development will be overseen.

The volume of the data streams to be processed, the necessary processing at each step in the data stream, the real-time processing needs, the need for redundancy, transmission bandwidth needs, online and mass-storage needs, etc. will be identified. A hardware schedule will be developed to support local and remote data processing and telecommunication between sites.

Sample data streams will be acquired from candidate field instruments and characterized, and a common data storage format will be developed.

Algorithms will be developed for data compression, common data format development, model interpretation of real-time data streams, and data-display routines for display of real-time data at the local computer facility. Data-access routines and methods to quality assure the data stream and provide online meta-data protection will be developed.

Quality-assurance procedures will be developed, and data documentation, procedures, standards, and online data catalogues for location and display of data sets will be produced. Project requirements for a data-base management system will be defined, and a commercial data-management package will be chosen to base development on.

Results to Date. We have contributed to conceptualizing and designing the CART data environment (CDE) and, in particular, the ARM data archives, which will be housed at ORNL. The CDE will collect, transport, store, and manage all of the ARM scientific data. The archives will manage and store between one and ten terabytes of data each year for each CART site, with additional storage of data during campaigns and when new instrumentation comes online. The archives will also be the contact point for all non-ARM scientists who want access to ARM data.

A conceptual design and implementation strategy have been developed that use existing computing systems at ORNL to provide the initial archival capability. This design calls for transferring the archival activity from shared computing resources to dedicated hardware within one to two years. Our plans for developing and operating the archives were presented to the JASON committee reviewing the ARM project in June of this year.

INTERFACING BETWEEN A HIERARCHY OF NUMERIC MODELS IN ARM

KAO, C. Y. JIM, and LEONE, JOHN

LOS ALAMOS NATIONAL LABORATORY
and LAWRENCE LIVERMORE
NATIONAL LABORATORY

FY 1991	400
FY 1990	0
FY 1989	0

11/01/90-09/30/91

Objective. To establish the relationship between the collective effects of clouds from cloud-scale simulations and the mean variables resolvable in GCMs.

Product. Methods for interfacing and data assimilation among a hierarchy of numeric models.

Approach. A hierarchy of models ranging from GCMs to mesoscale models to cloud models will be used to develop methods for data assimilation between the models as well as between models and field observations. The large-scale results of GCM calculations will be used to drive (or guide) mesoscale models that will subsequently provide input to the cloud models. The collective effects of clouds can then be derived from the detailed processes associated with the individual components of the cloud system and, in turn, related to the mean variables in the GCMs.

GCM parameterizations can thus be extensively tested against detailed, 3-D process models. The data-assimilation methodologies will allow ARM measurements, augmented with "numerical field experiments," to be incorporated into the models in a dynamically consistent way to increase the reliability and universality of GCM parameterizations.

Results to Date. We acquired the Colorado State University Regional Atmospheric Modeling System (RAMS) at the beginning of the project. The RAMS is a highly flexible model that can be used to simulate atmospheric circulations ranging from regional to cloud scales through a robust nested-grid capability.

We are currently implementing the Arakawa-Schubert scheme into the RAMS to investigate the parameterizability of midlatitude convective systems and to compare the results with those derived from a modified Kuo's scheme that has been a standard cumulus-parameterization scheme in the RAMS. The comparison is being done with the previous field experiment data, such as CCOPE and GATE. We will also be using the numeric data produced from the RAMS through explicit simulations of clouds with state-of-the-art cloud microphysics to verify and calibrate those parameterization schemes.

At the GCM to regional scale, we are currently using National Meteorological Center (NMC) global analyses to drive the RAMS to obtain the monthly climatology of the western United States. We will then turn on the nested-grid capability to further simulate the convective systems with the cloud microphysical modules.

WIDELY DEPLOYABLE LOW-COST RADIOMETER FOR THE ARM EXTENDED-OBSERVING STATIONS

KRYTER, ROBERT C.

OAK RIDGE NATIONAL LABORATORY

FY 1991	400
FY 1990	0
FY 1989	0

11/01/90-09/30/91

Objective. Design, develop, and demonstrate a customized radiometer for the ARM extended-observing stations that is superior in performance to presently available instruments and less costly to deploy, calibrate, and maintain.

Product. A field-tested prototype radiometer.

Approach. Sampling of the solar spectrum will be optimized to provide a full solar-spectral-curve (300 to 1100 nm) estimation from a relatively small set of measurements. Very-large-scale integration (VLSI) and computer-generated hologram (CGH) technologies will be used to realize a more reliable, maintainable, and rugged instrument while simultaneously reducing unit cost. And data-fusion concepts will be applied to best advantage for dynamic adjustment of measurement parameters, remote calibration, and fault detection. Photodetector arrays, radiometer circuitry, and the CGH will be designed, simulated, fabricated, and tested. Packaging for the radiometer will be designed and fabricated, and the unit will be laboratory and field tested.

Results to Date. We have devised a method for optimally partitioning the 300- to 1100-nm solar-measurement interval into a specifiable number (typically 38) of contiguous spectral bands of nonuniform width suitable for use with a photodetector array. The method is data driven (with either measured spectra or model predictions) and aims to equalize the

atmospheric-science information content of each of the measurement bands, such that spectral resolution is optimized, regionally, throughout the solar-measurement interval. Initial tests indicate that the accuracy with which a relatively high-resolution spectrum can be reconstructed from a scarce measurement set with this nonuniform band selection concept is improved at least 25% relative to the traditional use of uniform bandwidths.

Techniques for increasing the quantum efficiency of the photodetector array and for dramatically decreasing crosstalk have been studied, but have not yet been proven effective through laboratory tests. A custom integrated circuit having high sensitivity ($\sim 10^{-13}$A) and good linearity over a wide dynamic range (~7.5 decades) was designed and tested. A paper design for the entire optical front end of the radiometer was developed to our specifications by an optical-engineering specialty company. The design is based on a combination of conventional quartz-lens and unconventional holographic-optical-element (amacronic-lenslet) technologies, and will accommodate the nonuniform-width spectral-band selection.

SPECTROSCOPIC STUDY OF H_2O ABSORPTION IN THE 8- TO 14-μm ATMOSPHERIC WINDOW

KULP, THOMAS J.

LAWRENCE LIVERMORE NATIONAL LABORATORY

FY 1991	180
FY 1990	0
FY 1989	0

11/01/90-09/30/91

Objective. To provide an accurate characterization of atmospheric water-vapor absorption in the infrared transmission window at 8 to 14 μm.

Product. Data to fill in the gaps in the present empirical database regarding the 8- to 14-μm line and continuum absorption, and fundamental data on far-wing line structure that will contribute to an improved theoretical understanding of the water-vapor continuum.

Approach. This program will undertake laboratory measurements primarily with diode laser absorption spectroscopy and FTIR spectroscopy with a long-pathlength absorption cell. The line parameters of as many lines as possible in and around the window region will be quantified at various temperatures and pressures, and measurements will be compared with the results of HITRAN calculations. The dependence of the continuum absorption of water vapor on both temperature and wavelength in the window region will be quantified, and the results compared with previous measurements, where possible. The feasibility of using double resonance techniques to study individual, isolated rovibrational lines will be evaluated for characterizing the far-wing absorption in water-vapor absorption. Molecules that have simpler band structures than water will be measured to allow lineshapes to be observed under more isolated conditions than is possible with water.

Results to Date. A multipass absorption cell and its associated housing have been designed and assembled. The optical instrumentation necessary for the water-vapor-absorption measurements has been assembled, also. The absorption-cell optics are of the Horn-Pimentel design, having a 3-m base separation and allowing cumulative optical pathlengths up to 400 m. In our design, the cell mirrors are mounted on rigid pedestals that are firmly attached to a granite slab. The stainless steel chamber is suspended from a cradle to surround the cell optics while being mechanically isolated from them. This will minimize the effects of chamber motion on cell alignment caused by pressure and temperature changes. Adsorption of water vapor on the inner walls of the chamber is minimized by using mirror-polished stainless steel as the wall surface. The outer wall of the chamber can be heated or cooled by liquid circulation.

The optical instrumentation that was assembled for making the water-vapor-line measurements consists of a lead-salt diode laser spectrometer, which will be operated in the sweep-integration mode. Additionally, a BOMEM MB-100 FTIR was purchased to assist in the line measurements and to be used in continuum measurements.

ANALYSIS OF CLOUD RADIATIVE FORCING AND FEEDBACK IN A CLIMATE GCM

LACIS, ANDREW A.

GODDARD INSTITUTE FOR SPACE STUDIES

FY 1991	298
FY 1990	266
FY 1989	0

09/20/91-09/19/92

Objective. To refine and validate the GISS GCM radiation code through model intercomparisons and comparison with ARM observations; to refine and restructure the GISS GCM diagnostics to enable more informative comparisons to global radiation/cloud data sets; and to use ARM data to develop improved parameterizations of the radiative impact of clouds and to study the interaction of dynamics and radiation.

Product. An improved version of the GISS GCM with improved radiation codes and diagnostic codes that enable comparisons of model predictions with satellite data.

Approach. Observations and detailed models will be compared to the GISS GCM radiation code, thereby identifying differences and allowing improvement. Solar radiative codes will be improved, with special emphasis being placed on the water-vapor continuum and comparison of the GISS code to ARM measurements. Longwave radiative codes will be improved by comparing line-by-line calculations to HIS aircraft measurements and then comparing the GISS GCM radiation code to the line-by-line calculations; again, emphasis will be placed on the water-vapor continuum. The multiple-scattering treatment will be improved by developing a cloud-particle-size-dependent scattering algorithm. This treatment will be verified by comparison with HIS observations to separate the effects of multiple-cloud layering, cloud optical thickness, and particle-size variations. Emphasis will be placed on improving the treatment of cirrus clouds. This directly supports the objective of ARM to improve radiation parameterizations in GCMs.

The GISS GCM will be revised to output more diagnostics that can be compared with ERBE, ISCCP, and other satellite data. Cloud-related quantities will be saved during the GCM run, and the importance of spatial resolution of surface albedos will be examined. An offline 1-D code will be used to examine the importance of radiative-dynamic feedback responses. This work will provide a basis to extend ARM site-specific measurements to future satellite data sets.

The treatment of clouds in the GISS GCM will be improved through a series of sensitivity experiments with the GCM in which different aspects of the cloud physics will be varied. An offline 1-D model will be developed and used to compare the GCM cloud scheme to ARM data. This comparison will be used to improve the cloud scheme in the GCM. The modified cloud scheme, combined with the improved radiation schemes described above, will then be combined and verified against ARM data.

Results to Date. We have tested an improved cumulus and stratiform cloud scheme in the GISS GCM that provides for simultaneous deep and shallow convection; incorporates a cloud liquid/ice water budget; and includes a representation of mesoscale cumulus anvils, different microphysical properties for liquid and ice, and variable optical thickness. The results show enhanced upward moisture transport by the general circulation and increased water

vapor and ice injection at the cumulus-cloud top. We have developed a theoretical representation for the water-vapor continuum in the thermal window region of the spectrum.

We have also developed a 2-D radiative-convective-dynamical equilibrium model for diagnosing radiative and dynamical feedbacks in the GCM output results. To improve the treatment of multiple scattering by clouds and aerosols in the GISS GCM, we have developed a single-gauss-point adding and interpolating scheme to compute the effects of particle-size dependent clouds.

LASER REMOTE SENSING OF WATER VAPOR

LAPP, M.; MELFI, H.; and GOLDSMITH, J.

SANDIA NATIONAL LABORATORIES and NASA GODDARD SPACEFLIGHT CENTER

FY 1991	451
FY 1990	0
FY 1989	0

11/01/90-09/30/91

Objective. To extend Raman lidar technology to obtain vertical profiles of water vapor during both day and night.

Product. A prototype Raman lidar system with sufficient accuracy, reliability, and automation for inclusion in CART.

Approach. The detailed characteristics needed for a day/night-capable water-vapor probe at a CART site will be identified and defined. A complete optimization-analysis/instrument-performance model will be developed. The daytime probe upgrades will be designed and fabricated. Research and development will be supported for a Raman shifter for changing the wavelength of the candidate laser source; more-accurate determination of absorption cross sections for potential beam-absorbing gases; careful investigation of potential laser-induced fluorescence interference; and software. The daytime probe upgrades will be integrated into an existing Raman lidar system. The system will be field tested and used for model validation. The conceptual design and costing of a CART-ready system will be carried out.

Results to Date. An initial performance model has been developed for a daytime/nighttime Raman lidar that considers the key variables that affect the acquisition of water-vapor profiles in the troposphere. A primary focus for its use is to select the best choice of laser wavelength for daytime operation, which is found in the solar-blind region of the UV. Explicit consideration has been given to such factors as solar irradiancy, potentially interfering absorption lines, etc. To test the model results, a mobile Raman lidar has been developed to evaluate the optimization issues found significant by the performance model. This lidar uses an excimer laser operating at 248 nm for daytime and 351 nm for nighttime operation, with eight channels of data for each: elastic scattering and N_2, O_2, and H_2O Raman scattering at high and low sensitivity. In situ data for determining O_3 absorption corrections are provided. An upgraded data-reduction model has been developed, enabling the lidar to operate efficiently in the field. The characteristics of the laser source have been studied experimentally, as have those of Raman wavelength shifters for the high-power 248-nm beam.

ARM SUPPORT

LEIFER, ROBERT

ENVIRONMENTAL MEASUREMENTS LABORATORY

FY 1991	415
FY 1990	0
FY 1989	0

12/01/90-09/30/91

Objective. To develop specialized sampling equipment for the characterization of the aerosol associated with energy-related and radiatively active pollutants in the atmospheric boundary layer and the free troposphere.

Product. An understanding of the vertical distribution of aerosol in the lower 1 km of the atmosphere.

Approach. Filter and gas samplers and a multi-wavelength nephelometer will be developed for use on small, tethered balloons; and a thermally activated condensation-nuclei counter will be developed for the characterization of sulfate-bearing aerosol.

Results to Date. EML's integrating nephelometer was recently tested at the Grand Bahama Island (GBI) site. The nephelometer and our automated condensation nuclei (CN) counter were mounted on the U.S. Coast Guard's Aerostat. This package provided real-time atmospheric measurements (every 15 seconds) of the particle-number density and scattering coefficient from the ground to 3 km. Preliminary analysis of the data indicates production of small particles (0.02 to 0.1 μm) occurring frequently over the site. We will continue to extend the lower limit of detection of the nephelometer and to modify its operation for use on small, light-weight tethered balloons. The CN counter worked well and is being modified for sulfate-particle counting.

A small, single-stage impactor was built and successfully operated at the GBI site. These samplers can be mounted on large or small tethered lines. A new sampling package is under development that contains not only the impactor but also a temperature and humidity sensor, a pressure transducer, and a minicomputer. This package is capable of being lifted by small, tethered balloons.

Our aerosol sampler containing 24 filter cassettes has been modified to allow easier control by the onboard computer.

TESTBED MODEL AND DATA ASSIMILATION FOR ARM

LOUIS, JEAN-FRANCOIS

ATMOSPHERIC AND ENVIRONMENTAL RESEARCH, INC.

FY 1991	163
FY 1990	161
FY 1989	0

09/15/91-09/14/92

Objective. To develop and apply methods of data assimilation for the ARM testbed data on a scale consistent with climate models and to design and implement a model for the testing of parameterizations of cloud characteristics and radiative-transfer processes important in global climate change

Product. Methods to effectively test parameterizations suitable for use in general-circulation models (GCMs) by the analysis of the large amounts of data that will be produced at ARM testbed sites and by sensitivity tests of GCM components.

Approach. A 1-D model, the AER Local Forecast Adaptation (ALFA) model, will be further developed and will be used to simulate conditions at ARM testbed sites in the same manner as does a GCM over a single grid cell. The 1-D model will be constructed to include the framework by which ARM researchers can test interactive modules that contain the necessary parameterizations [e.g., on radiative transfer, cloud microphysics, and the dynamics of the atmospheric boundary layer (the lower 2 km of the atmosphere)].

The ARM data, together with analysis results from the National Meteorological Center, will be assimilated with the ALFA model to produce a continuous description of the atmosphere above the ARM site. The "adjoint" method will be used to ensure that differences between observations

and the evolving variables computed with ALFA are minimized.

The means to conduct sensitivity studies on parameters important in GCM modules will be developed from a form of the adjoint method. As a test case, the sensitivity of the Toon-Ackerman radiation model to various cloud parameters will be evaluated.

Results to Date. We have obtained a copy of the source code of the Toon radiation model and have written the adjoint of this code (i.e., writing the perturbation equations corresponding to each model equation, writing the adjoint of these equations, and reorganizing the code so that the operations are done in reverse order). We developed tools to ease the development of the adjoint and to test its accuracy. This work is now finished. During the remainder of the period, we will develop the structure of the data-assimilation system.

GROUND-BASED MILLIMETER-WAVELENGTH CLOUD-PROFILING RADAR SYSTEM (CPRS)

McINTOSH, ROBERT E.

UNIVERSITY OF MASSACHUSETTS

FY 1991	319
FY 1990	315
FY 1989	0

09/15/91-09/14/92

Objective. To develop a millimeter-wavelength radar for cloud-field mapping that helps distinguish between scattering and absorption processes.

Product. A remote sensing system that fills a gap in the penetration-backscatter-strength tradeoff and can yield information on the water-ice ratios of cloud water substance, profiles of cloud-water amount, backscatter/absorption ratios, and vertical velocities in clouds.

Approach. A millimeter-wavelength-radar instrument will be developed that uses two wavelengths selected to help distinguish between scattering and absorption processes. Measurements of the polarization of the return signal will assist the interpretation of water to ice ratios and the Doppler shift in the return will indicate vertical velocity, a crucial quantity for cloud formation. Existing airborne millimeter-wave designs will be used as a basis for this high-power, ground-based mobile facility.

Results to Date. The subsystems for the cloud-profiling radar system, a two-frequency (35 and 95 GHz) polarimetric radar with a single reflector-lens antenna, are currently being developed and tested.

The 95-GHz polarimeter was tested at the University of Massachusetts, and calibrations show that the rms phase noise at 1 km is less than 2^{o} and the sensitivity corresponding to a unity signal-to-noise ratio allows us to see a -21 dBz target at a range of 1 km without averaging. This sensitivity was achieved with 12-in. transmitter and receiver antennas, a 2-MHz receiver bandwidth, and a 500-ns transmit pulse. Corner reflector measurements show that >30 dB of isolation exists between the vertically and horizontally polarized channels.

The 35-GHz polarimeter's design has been completed, and components are currently being purchased. The critical part of the new design is the high-power transmitter that will transmit up to six polarizations at approximately 90 kW peak power.

A dual-frequency (35 and 95 GHz) single reflector-lens antenna has been designed for the radar system. The antenna will use a 35-GHz scalar feed horn with a 95-GHz dielectric-rod antenna running down the center of the horn. This feed has the attractive feature of being a single, compact, and rugged design to transmit both polarizations of the 35-GHz and 95-GHz signals. The horn will illuminate a 1-m-diam dielectric lens.

DEVELOPMENT OF ROTATING SHADOWBAND SPECTRAL RADIOMETERS AND GCM RADIATION-CODE TEST DATA SETS IN SUPPORT OF ARM

MICHALSKY, J., and HARRISON, L.

STATE UNIVERSITY OF NEW YORK AT ALBANY

FY 1991	249
FY 1990	257
FY 1989	0

09/15/91-09/14/92

Objective. To develop a high-quality data set of cloud- and/or aerosol-modified direct and diffuse solar irradiances that would enable development of improved GCM parameterizations, to develop a filter-based rotating shadowband radiometer (RSR) suitable for use at CART extended sites, and to develop a CCD-array based RSR suitable for use at the CART central site.

Product. Ground and satellite data related to direct and diffuse solar irradiances assembled in a common database and prototype RSR instrumentation to be delivered to and evaluated at the first CART site.

Approach. Existing ground-based radiation and meteorological data sets of high quality will be assembled that can be used in conjunction with existing satellite data to provide modelers with a basic data set for refining the cloud/radiation models in current GCM codes.

The data quality and comprehensiveness of existing ground-based data is anticipated to fall short of what modelers will need. To provide modelers with improved data until the CART sites produce data, an observational program will be conducted to add key parameters measured at a single site in upstate New York.

Two variants of the rotating shadowband radiometer (RSR) will be developed, carefully tested, and deployed; they will measure the spectrally resolved direct and diffuse irradiances. One of these instruments will measure the irradiance in seven discrete spectral intervals of 10-nm (or greater) half-width selected within the range 380 to 2500 nm; the other will measure the irradiance in 256 wavelength intervals nonlinearly distributed over the range 350 to 1050 nm, providing a spectral resolution of 0.6 nm at the blue end of this spectrum and 10 nm at the infrared end. The first instrument is intended to fill the needs of the Extended-Observing Network of each CART, and the second is proposed for the Central Site.

Results to Date. High-quality, 15-minute solar-radiation data from Albany, New York, and Golden, Colorado, have been combined with hourly surface observations and 12-hourly upper air data from National Weather Service sites. These data form a data base suitable for testing some aspects of radiation codes used in global climate models. Data are available for selected months in 1986 and 1987.

A new measurement program was begun in Albany in July 1991 to add shortwave ground albedo, downwelling longwave, and total column aerosol optical depth to the usual solar measurements of global horizontal and direct normal shortwave irradiance.

Nine seven-filter rotating shadowband radiometers have been deployed in a related DOE program. The ARM units use a slightly different filter set. The detector head contains a cubic circuit board that encompasses the detectors and amplifies their small currents. The head is controlled at 35°C. Key to its operation is a new integrating cavity-diffusing disk cosine receptor whose response is acceptable for most solar angles. Also important to this task was the development of a cosine bench for the automated and repeated testing of cosine responses.

ARM TROPICAL PACIFIC EXPERIMENT (ATPEX): ROLE OF CLOUD, WATER-VAPOR, AND CONVECTION FEEDBACKS IN THE COUPLED OCEAN/ATMOSPHERE SYSTEM

RAMANATHAN, V., and BARNETT, T.

SCRIPPS INSTITUTION OF OCEANOGRAPHY

FY 1991	528
FY 1990	0
FY 1989	0

08/01/91-07/31/92

Objective. To observe and model the radiative feedbacks and energy fluxes in the tropical western Pacific and to use this understanding to advance climate model development.

Product. An increased understanding of the enhanced greenhouse effect and the role of clouds in modifying the effect.

Approach. Data processing and imaging techniques will be developed to combine ARM data with satellite data. The work will be closely coordinated with the ARM Science Team to assure that the satellite data and the ARM data complement each other as well as provide the data essential for testing the hypothesis of the super greenhouse effect in the tropical western Pacific. The satellite data will include atmospheric profiles of temperature and humidity, estimates of total water vapor, and 3-D radiative information for cloud research.

A coupled ocean/atmosphere GCM will be used to seek understanding of the measurements and to assist in selecting the elements to be measured. The model will be used to assist in validating and advancing the cloud-radiation parameterizations used in GCMs, with emphasis on the role of tropical convection. The seasonal cycle and the El Niño/Southern Oscillation data (including the satellite data) will be used in conjunction with the model. The hypothesis is that a "super" greenhouse must be induced by the unique energy balance, with the clouds regulating the sea surface temperature yet owing their existence to the warm SSTs and the convection.

State-of-the-art, 3-D visualization will be used in both tasks to aid in the understanding of the separate products of each task and the comparison of the data and model information.

HIGH-SPECTRAL-RESOLUTION RADIANCE MEASUREMENTS FOR THE ARM PROGRAM

REVERCOMB, H.

UNIVERSITY OF WISCONSIN

FY 1991	519
FY 1990	358
FY 1989	0

09/15/91-09/14/92

Objective. To design and deliver three instruments to CART sites to provide the highly accurate observations needed for detailed comparisons with line-by-line calculations (such as FASCODE3) and for determining the radiative characteristics of clouds, aerosols, and trace gases.

Product. Fourier-transform infrared-spectroscopic expertise and instrumentation to support the improvement of high-resolution line-by-line radiative-transport codes and to improve the physical understanding of longwave radiation transport in the atmosphere.

Approach. Three instrument types will be developed to provide the highly accurate observations needed for detailed comparisons with line-by-line calculations and for determining the radiative characteristics of clouds, aerosols, and trace gases. Two will make highly accurate measurements of the atmosphere-emitted

radiation (AERI and AERI-X), and the third (SORTI) will measure the atmospheric transmission to high accuracy with observations of the sun at different air masses.

The AERI (atmospheric emitted radiance interferometer) instrument will operate over the spectral range of 4 to 20 microns (2500 to 500 wavenumbers) at a resolution of 1 wavenumber. It will be sufficiently inexpensive to be deployed throughout the ARM networks and, as such, will provide the link of point measurements to the larger scale. A system of AERI instruments would also provide important 3-D measurements of meteorological parameters in the lower atmosphere.

The AERI-X instrument will provide improved spectral resolution (0.1 wavenumber) over the wavelength range of 4 to 20 microns. It will provide the higher spectral resolution needed at a more limited number of locations to acquire the best available emission observations for comparison with line-by-line calculations.

The Solar Radiance Transmission Interferometer (SORTI) measurements with a resolution of 0.002 wavenumber will yield the atmospheric transmission at essentially full resolution. It will reveal deficiencies in the way model calculations handle absorption line shapes and line interactions. Prototypes of all instruments will be delivered for testing at the first CART site in 1992.

Results to Date. Design concepts have been verified for the AERI, AERI-X, and SORTI. The AERI and AERI-X will require accurate calibration procedures integral to the system designs. These concepts have been extensively tested with a complete development system. Tests included the successful participation in the WISP/ARM field experiment at Platteville, Colorado, in March 1991. Key instrument subsystems extensively analyzed with the development system include the black-body-heater controller, the temperature-monitoring system, the scene-switching-mirror controller, and the interferometer-data ingest and formatting functions. In addition, software has been written to provide real-time calibrated products within minutes of the atmospheric observations. The black-body cavities used in the development system have been carefully modelled with a thermal-analysis program validated with laboratory test data. This model has been extrapolated to the larger black-body cavities required for the AERI and AERI-X systems while maintaining a high degree of temperature uniformity. In addition, the highest-resolution interferometer hardware has been extensively tested in comparison with BOMEM and BRUKER products. Both instrument options demonstrated the sensitivity needed for the SORTI and AERI-X instruments.

CLOUD AND AEROSOL CHARACTERIZATION FOR THE ARM CENTRAL FACILITY: MULTIPLE-REMOTE-SENSOR TECHNIQUE DEVELOPMENT

SASSEN, KENNETH

UNIVERSITY OF UTAH

FY 1991	184
FY 1990	344
FY 1989	0

09/15/91-09/14/92

Objective. To develop and deploy a combination of active and passive remote-sensing systems to observe features of clouds that are crucial to ARM, including cloud water/ice ratios, crystal shape and orientation, and cloud optical properties and to develop empirical and cloud-model-based algorithms for the remote-sensing characterization of the cloud atmosphere.

Product. Measurements and interpretation with polarization diversity lidar, 8-mm radar, IR and visible radiometers, all-sky video imager, and other instruments.

Approach. A polarization diversity lidar (PDL) will be developed that will use two wavelengths with parallel and orthogonal polarization components to enhance observation of cloud distribution and type, cloud structure, cloud ice/water ratio, crystal shape and orientation, and cloud optical properties. The system plus two supporting passive remote sensing systems (an infrared radiometer and an all-sky video imaging system) will be deployed in conjunction with NOAA equipment in a field experiment to compare multiple-sensing-system findings.

Interpretation of the data will be conducted in collaboration with the broader ARM research community to design future needs for ARM's continuous Cloud and Radiation Testbed (CART) operations.

Results to Date. PDL design innovations have made possible scanning, dual-receiver, four-channel data acquisition at 10 Hz PRF, with variable field-of-view capabilities, for two-color linear depolarization or monochromatic four-channel Stokes parameterizations. PDL deployments at the upcoming Project FIRE IFO cirrus cloud experiment and for campaigns at CART locales are planned. Evaluations of multiple-remote-sensor approaches have involved lidar and mid-infrared radiometer data collection at the University of Utah Facility for Atmospheric Remote Sensing and an impressive ensemble of NOAA Wave Propagation Laboratory instruments with research aircraft support during the recent CLARET II field experiment. Supporting numeric experiments include a variety of theoretical and empirical studies.

SITE SELECTION, CAMPAIGNS, AND DATA AUGMENTATION

SCHWARTZ, STEPHEN.E.

BROOKHAVEN NATIONAL LABORATORY

FY 1991	159
FY 1990	500
FY 1989	0

10/01/90-09/30/91

Objective. To identify sites for conducting measurements of atmospheric radiation and controlling properties and processes, to identify sites and situations suitable for conducting specialized measurement campaigns, and to develop procedures for obtaining data from other programs and agencies needed to meet ARM objectives.

Product. Specification of requisite attributes of ARM site and site-selection procedure; identification of candidate sites and situations suitable for specialized ARM field measurement campaigns; identification of external data necessary to meet ARM Program objectives and approaches to acquire these data.

Approach. By canvassing leading scientists in the field, lists will be prepared of potential ARM sites based on scientific an logistical considerations, including coordination with activities of other agencies. The lists will represent incremental additions of up to six sites.

A similar procedure will be followed to formulate a list of options for ocean ARM sites. Those consulted will include leading academic scientists and investigators and administrators in other national laboratories, other federal agencies, and universities. The site-selection team will provide DOE information on establishing and maintaining an ocean ARM site, the instruments that may be supported

continuously from various platforms, and a cost estimate for an ocean site and campaign support.

The modeling community will be consulted to determine quantities to be measured, conditions under which measurements should be made, and accuracy and precision requirements for the data. The remote-sensing community will be consulted to determine the needs for in-situ measurements to evaluate and supplement remote-sensing measurements. Other agencies and programs will be consulted to identify sites and projects suitable for coordinated efforts.

As a consensus develops on the data requirements, an evaluation of measurement facilities will be conducted.

The operation plan will include a statement of the objectives of the program, including a rationale for the measurements that will be conducted and a statement of the expected output of the program; a description of the instruments and facilities that will be used in the program; flight plans; a data-management plan; and a quality-assurance plan.

Data needs, sources of these data outside the program, and means of acquisition and dissemination (including archiving) will be identified.

Results to Date. No results reported.

PARAMETERIZATIONS FOR INTEGRALS OF RADIATION'S EFFECTS ON CLOUDS, SURFACES, AND STABILITIES

SLINN, W. G. N.

PACIFIC NORTHWEST LABORATORY

FY 1991	80
FY 1990	0
FY 1989	0

11/01/90-09/30/91

Objective. To develop the scientific concepts surrounding the integral approach to the use of the Clouds and Radiation Testbed (CART) for significantly reducing the uncertainties in current parameterizations of important radiative-transfer processes for use in GCMs and related models.

Product. Specific methods and measures for applying the integral approach to improving parameterizations of radiative-transfer processes associated with cloudy skies and inhomogeneous surfaces.

Approach. Empirical solutions to radiative-transfer problems will be sought with integral measures as opposed to differential measures. Because nature integrates over all details and effectively only highly integrated approaches can be used in GCMs, this approach may offer a unique approach to the design of experiments and campaigns. The project will focus on identifying those variables that represent nature's integrations over many complicated variables and processes and on developing the concepts and methods for incorporating such variables into improved parameterizations that will characterize radiation's effects on clouds and stability.

Results to Date. Based on simple models, reports are being prepared on modeling needs (for model developments by the ARM modeling team) and on measurement needs at the first ARM-CART site.

DIAGNOSTIC MODELING OF THE ARM EXPERIMENTAL CONFIGURATION

SOMERVILLE, RICHARD C. J.

SCRIPPS INSTITUTION OF OCEANOGRAPHY

FY 1991	119
FY 1990	110
FY 1989	0

09/15/91-09/14/92

Objective. To test parameterizations of cloud formation that are currently in use in general-circulation models (GCMs) with data gathered by ARM.

Product. A better understanding of the validity of various parameterizations in use in GCMs.

Approach. The research will use a 1-D diagnostic model of a single GCM grid and combine measurements of initial conditions and horizontal transports made at the ARM site with the model to predict cloud formation and characterization. The prediction of clouds by the model will use the parameterizations in use in GCMs. The resulting predictions will be compared to the ARM measurements to test the accuracy of the cloud parameterizations. The relative merits of a variety of competing parameterizations will be studied. Thus, the research will provide improvements and alterations to the existing 1-D diagnostic model; diagnostic modeling, wherein ARM data and the predictions of various parameterization schemes are compared; and new knowledge for improving the cloud-modeling aspects of the GCM.

Results to Date. We have generalized the model to an arbitrary number of levels, changeable by adjusting a single parameter. We have also developed a flexible interface with graphical display software and other postprocessing applications.

We have developed and implemented a more general parameterization of the bulk-exchange coefficients based on the work of Liu et al., replacing our earlier version of the bulk-aerodynamic-surface-exchange formulas. The soil-moisture treatment of Deardorff has been included in our model, which will allow the model to be applied under a variety of soil and vegetation conditions.

We have also incorporated the cumulus-convection scheme of Arakawa and Schubert into our model. The new convection parameterization is not intended to replace the existing Kuo-Anthes scheme. Rather, we intend to use the ARM data to test these alternative parameterizations within the model.

Preliminary work is in progress to include a more thorough and complex treatment of the atmospheric boundary layer based on the 3-D, second-order turbulence-closure model of Yamada.

A STOCHASTIC FORMULATION OF RADIATIVE TRANSFER IN CLOUDS

STEPHENS, G. L., and GABRIEL, P.

COLORADO STATE UNIVERSITY

FY 1991	75
FY 1990	69
FY 1989	0

09/15/91-09/14/92

Objective. To develop new theoretical methods for describing radiative transfer in inhomogeneous clouds and cloud fields and for analyzing cloud and radiation data.

Product. Basic insights on radiative transfer in clouds and, potentially, methods to achieve the parameterizations required by large-scale atmospheric numeric models to describe the radiation balance.

Approach. Simple mathematical relationships will be developed between the statistical moments of the radiation field and those of the optical properties of clouds, mainly on the basis of results obtained with a two-stream radiation model applied in a plane-parallel medium. Cloud optical depth will be the primary independent variable. More-sophisticated mathematical relationships will be derived that describe the influence of the statistics of the horizontal structure of clouds on the radiative transfer through them. Data obtained from satellites and aircraft as well as from ground stations will be used to develop a measure of the statistics of

horizontal variability of cloud properties. Histograms of the reflectance and transmission properties will be produced with the Ricatti equation, whose solutions will be constructed and manipulated with advanced mathematical techniques.

Simple relationships will be constructed suitable for parameterizing cloud-radiation interactions in GCMs, particularly on the transmission, absorption, and reflection of radiation as a function of cloud parameters that can be produced in GCMs.

Results to Date. The problem of deterministic radiative transfer in multidimensional media and stochastic radiative transfer in a 1-D medium whose inherent optical properties are described by a probability distribution is being investigated. Deterministic multidimensional radiative transfer is formulated in terms of a local interaction principle expressed in Fourier space. This formulation leads to a system of Matrix-Ricatti equations that are solved with Runge-Kutta solvers for the global response, subject to arbitrary boundary conditions. The computer code that performs these calculations is operational and is being optimized. Various issues concerning the scale-dependence of the radiation field on inhomogeneous cloud distributions are being explored. The Fourier approach to radiative transfer has also led to a new formulation of atmospheres exhibiting only horizontal variability. In that case, no differential equation is solved.

Stochastic radiative transfer is being approached in two ways. In one, the solution of the equation of transfer is weighted by an appropriate probability distribution and, under certain conditions, the probability distribution for the intensity can be derived. The second, a more general approach, uses the concept of a stochastic Greens function from which the moments of the radiance are calculated.

ATMOSPHERIC RADIATION MEASUREMENT PROGRAM (ARM)

STOKES, GERALD M.

PACIFIC NORTHWEST LABORATORY

FY 1991	8107
FY 1990	4000
FY 1989	0

10/01/90-09/30/91

Objective. To improve the performance of general-circulation models (GCMs) of the atmosphere for global and regional climate prediction through improvements in the treatment of radiative-transfer models in GCMs under clear-sky, general-overcast, and broken-cloud conditions and in the parameterization in GCMs of cloud properties, cloud formation, and cloud maintenance.

Task I. ARM Management (Gerald Stokes, Pacific Northwest Laboratory; Marvin Dickerson, Lawrence Livermore National Laboratory; Paul Kanciruk, Oak Ridge National Laboratory; Tihomir Novakov, Lawrence Berkeley Laboratory; Blair Burner, WISDM Corporation; David Sowle, Mission Research Corporation; and Robert Ellingson, University of Maryland)

Product. The management of the ARM Program and the development of its experimental infrastructure, known as the Clouds and Radiation Testbed (CART), to provide a basis for the detailed testing and verification of the modeling of subgrid processes in GCMs, the ability to rapidly deploy experiments to the field, and a strong coupling to the scientific goals of the program.

Approach. The ARM program will be managed from the ARM Project Office, located at the Pacific Northwest Laboratory and consists of three distinct entities: the Science Team, the Instrument-Development Program, and the Clouds and Radiation Testbed.

The Project office will provide central planning and management for the ARM program, support of the DOE/OHER Environmental Sciences Division's activities, and coordination of the ARM program activities with related technical activities in other agencies and countries.

The Science Team will conduct approved research projects; provide basic guidance for the selection of sites, common modeling activities, and instrument selection; and set the scientific direction of the ARM program.

The Instrument-Development Program will provide for the long-term, high-risk development of critical technologies of interest to ARM, and it will provide a directed instrument-development activity when an instrument must be developed to meet a need within ARM that cannot be met by other means.

The Clouds and Radiation Testbed (CART) will be the basic experimental infrastructure for the ARM program. The CART itself will consist of several permanent observing stations; some mobile measurement capability; support for intensive campaign activities either at a fixed ARM site or in collaboration with related programs; and a data system that supports the above activities, the acquisition of other related data, and the analysis of these data by the Science Team.

The CART will be developed by several interlaboratory teams related to the data system, modeling, instruments, site selection, and site operations. Each team will be headed by a principal investigator from a DOE national laboratory.

Results to Date. The first DOE solicitation for research grants in support of ARM resulted in 39 grants, the principal investigators of which formed the nucleus for the ARM Science Team. The first Science Team meeting was held in November 1990, and a major recommendation to flow from the meeting was the need for an integrated Science Plan. The Science Plan is now in draft form and is being reviewed by members of the Science Team.

The Site Management Plan was developed in conjunction with DOE Headquarters and resulted in the designation of the Site Program Manager and Site Scientist positions. Site scientists for all but one site were named in the Spring of 1991.

An implementation review was conducted at PNL with members of the Science Team and the newly selected Site Program Managers, and a full technical review was conducted by the JASON group.

Programmatic collaborations have been developed with the First ISCCP Regional Experiment (FIRE); the Global Energy and Water Experiment (GEWEX); and the Tropical Ocean, Global Ocean (TOGA) program.

Task II. Site Operations Team (Sumner Barr, Los Alamos National Laboratory; Gerald Stokes, Pacific Northwest Laboratory; Marvin Wesely, Argonne National Laboratory; John Vitko, Sandia National Laboratories; and Paul Kanciruk, Oak Ridge National Laboratory)

Product. Management of the site-operation activities within the infrastructure of ARM and overseeing of the operation of individual sites by site-operation contractors.

Approach. The Site Operations Team will serve as a bridge between activities that lead to the development of CART and the Site Program Manager and Site Operator of the individual ARM sites. The team will develop the initial site operations plan for each site and train operations personnel during the site deployment. Finally, the team will transfer the site, its associated equipment, and the maintenance of the site operations plan to the Site Operator and the Site Program Manager.

Results to Date. Teams were formed to consider the locale recommendations of the Site Selection

Team. An analysis report for the five locales suggested (Southern Great Plains, Tropical Western Pacific Ocean, Eastern North Pacific/Atlantic, North Slope of Alaska, and the Gulf Stream) is in draft form and being reviewed by the Science Team. The Southern Great Plains was recommended as the first site because of the range of cloud and radiation conditions that occur there, the existence of extensive atmospheric instrumentation, the existence of other research programs with which collaborations could be formed, and the logistical supportability of a site in that area.

Within the Southern Great Plains region, instrument distributions, airspace usage, land usage, and terrain are being evaluated to narrow down to the best location for the central measurement facility. Subsequently, other measurement-facility sites will be selected. NEPA screening has been a major task, and the Action Decision Memorandum necessary to establish the process for an Environmental Assessment to support a Finding of No Significant Impact (FONSI) is in coordination and near approval.

Task III. Modeling Team (Marvin Dickerson, Lawrence Livermore National Laboratory; Gerald Stokes, Pacific Northwest Laboratory; and Stephen Schwartz, Brookhaven National Laboratory)

Product. Management of the modeling activities within the infrastructure of ARM and the development of a system that supports the testing of models within the ARM data system, including the verification of model parameterizations against ARM observational data sets.

Approach. The Modeling Team will design a set of general measurement strategies that encompass the measurement needs of the Science Team; refine measurement designs to meet modeling needs to confirm consistency of initial ARM radiative-flux measurements against theoretical calculations; specify the support required by modelers from the ARM data system for experimental and operational models; and maintain operational support models for use by the general ARM research community. The Modeling Team will identify, prepare, and hand off operational support models to the Data Management Team; conduct sensitivity studies in support of the identification of observational precision and accuracy requirements; and develop a method for comparing model performance and a method for the integration of ARM results with other modeling activities (e.g., the Program for Climate Model Diagnostics).

Results to Date. General measurement strategies have been developed for the instantaneous radiative flux, single-column GCM, and 4-D data-assimilation cases and are being readied for review and discussion by the Science Team. In the course of developing these strategies, the Team addressed the issue of what operational support models must be available to users of the CART data system for a wide variety of needs from data manipulation to the evaluation of a parameterization. These models will become part of the catalog of models available to every user. Surrogate data sets (e.g., 4DDA) have been acquired and are being set up for access by the general ARM community to facilitate evaluation of data-transfer and model-evaluation techniques prior to operational data acquisition in 1992.

Task IV. Site Selection Team (Stephen Schwartz, Brookhaven National Laboratory; and Gerald Stokes, Pacific Northwest Laboratory)

Product. Management of the site-selection activities within the infrastructure of ARM and identification of potential relationships between ARM and other experimental programs.

Approach. The site selection will be designed to be conducted in three stages. First, a scientifically defensible set of general geographic regions that would collectively meet the ARM goals will be identified. Then, in collaboration with the operations team, detailed analyses will be prepared as background for the final site

selection. Final selection of the sites will be made upon recommendation of the Site Program Manager and the Site Scientist.

Results to Date. The scientific analysis of the possible geographical locales in which to conduct ARM operations is complete, and a peer-reviewed version of that report has been released. Five primary locales (Southern Great Plains, Tropical Western Pacific Ocean, Eastern North Pacific/Atlantic, North Slope of Alaska, and the Gulf Stream) were recommended, and several supplementary locales identified. Locale specific reports are in draft form and undergoing review. Climatological analyses have been conducted in support of the studies necessary to determine the location of the first site in the Southern Great Plains locale.

Task V. Instrument Team (Marvin L. Wesely, Argonne National Laboratory; Gerald Stokes, Pacific Northwest Laboratory; John Vitko, Sandia National Laboratories; Roland Hulstrom, Solar Energy Research Institute; Gary Parks, Jet Propulsion Laboratory; John DeLuisi and Brooks Martner, NOAA/Climate Monitoring and Diagnostics Laboratory; and Kenneth Gage, NOAA/Wave Propagation Laboratory)

Product. Management of ARM infrastructure activities concerning instrumentation and the identification and installation of observation systems necessary to meet the requirements for data to test numeric-model components being developed for use in GCMs.

Approach. Argonne National Laboratory will lead an interlaboratory instrument team whose tasks will be to identify and evaluate technologies for possible incorporation in observation systems of the Clouds and Radiation Testbed (CART) of ARM; to develop the initial operational and calibration protocols for each equipment item before transferring it to individual ARM site operators; and to provide technical information to support the acquisition of instruments for ARM sites and the ARM mobile system.

Results to Date. A planning session on instrument selection procedures was held with representatives from the ARM instrument team, project office, science team, instrument development program, site selection and campaigns team, and operations team. These procedures have been documented and partially implemented to select an initial complement of instruments at the first ARM/CART site. These procedures have been reviewed by the ARM management, functional, and science teams. The initial instrument complement emphasizes observations made at a land surface and includes surface-flux stations to observe air-surface exchange of moisture, heat, and momentum; balloon-borne sounding systems to obtain vertical profiles of wind speed, temperature, and humidity; microwave radiometers to observe vertical integrated columnar amounts of water vapor and liquid; and radar wind-profiler systems coupled with acoustic systems to observe vertical profiles of mean wind-velocity components and temperature. The instrument team and the operations teams have worked together to propose various methods of deploying the planned surface observational systems.

Task VI. Data Management Team (Ronald B. Melton, Pacific Northwest Laboratory; Marvin Wesely, Argonne National Laboratory; Stephen Schwartz, Brookhaven National Laboratory; John Vitko, Sandia National Laboratories; Paul Kanciruk, Oak Ridge National Laboratory; and Lawrence Rothman, Philips Laboratory).

Product. Management of ARM infrastructure activities concerning the design, development, and deployment of an integrated data system to support the acquisition, manipulation, analysis, archiving, and distribution of ARM data

Approach. A multilaboratory team, including the participation of Oak Ridge, Argonne, Brookhaven and Sandia national laboratories, will use a top-down design method and a phased-implementation strategy for the development of the system. The design strategy will be based on the same approach used by the

overall project and will provide for positive integration with the rest of the project.

Results to Date. The results of a detailed design session conducted in FY 1990 have been used as the basis for dividing the data-management task into a series of whole systems for which conceptual-design strategies have been drafted. The conceptual designs are now being used to drive the further design and implementation strategy. The phased implementation calls for three basic systems associated with the site, science team support, and archives. An agreement has been reached with the National Center for Atmospheric Research to use their "zeb" system as the basis of the implementation of the site and science-team support systems. Preliminary capacity requirements and hardware requirements for the first site have been determined.

MODELING CLOUDS AND RADIATION FOR DEVELOPING PARAMETERIZATIONS FOR GENERAL-CIRCULATION MODELS

TOON, O. B., and WESTPHAL, D.

NASA AMES RESEARCH CENTER

FY 1991	209
FY 1990	120
FY 1989	0

09/30/91-09/29/92

Objective. To develop practical parameterizations for treating cirrus and stratus clouds in global-scale models; to develop new, accurate treatments of radiative transfer; and to study these schemes and the ability of high-resolution, large-scale models to simulate the development of cirrus clouds by applying these parameterizations in a 3-D mesoscale model.

Product. A new parameterization for treating cirrus and stratus clouds in a GCM and more accurate treatment for radiative transfer.

Approach. A hierarchy of models will be developed and tested so that the accuracy of both the radiation model and the cloud model can be determined. A 4-D data-assimilation analysis package will be developed to allow the mesoscale model to more correctly match observed variables at the ARM sites. The mesoscale model and 4-D data-assimilation scheme will be used to investigate intensive observational studies at ARM sites and to test the ability of dynamical models to properly reproduce moisture fields. The mesoscale model will also be used with different cloud-microphysics parameterizations and compared to observations at the ARM sites to test the cloud parameterizations.

Absorption coefficients will be developed with the exponential-sum approach. This approach will be extended to treat overlap regions of different gases and inhomogeneous atmospheres. The choice of coefficients will be tested with line-by-line techniques. Other fast radiation-transfer techniques will be developed and tested to see if they are more accurate than the two-stream approach. Also, techniques will be adopted for treating the spherical nature of the atmosphere in a simple manner. The radiation models will be tested against ARM data, and new absorption coefficients will be derived as needed. Radiation codes will be developed to compare the mesoscale-model output with intensity observations. And radiation codes will be developed and tested that consider the effects of broken cloud fields at both the mesoscale-model scale and the GCM grid scale.

Cloud microphysical parameterizations will be developed for cirrus and status clouds that are appropriate for use in GCMs. The marine stratus model will be used to investigate how the albedos and latent-heat release of marine stratus vary in response to changing environmental conditions. Parameterization schemes will be developed for marine stratus in GCMs. The 1-D cirrus/aerosol model will be applied to study tropospheric cirrus clouds and the development of vertical variations in the size distribution of

ice crystals. Parameterizations of ice will be evaluated with bulk fall speeds. The effects of optical and microphysical properties of ice crystals on the generation of cirrus will be studied. The sensitivity of cirrus radiative properties to the large-scale dynamical properties in the atmosphere will be determined. The the minimum resolution of the size distribution needed to match observations and retain an adequate representation of the original model at full resolution will be determined to develop a simplified model that is suitable for inclusion in the mesoscale model. And cloud microphysical parameterizations in the mesoscale model will be tested by comparing the model results to measurements at ARM sites.

Results to Date. The mesoscale model with coarse and fine grid resolutions of 70 and 23 km, respectively, and with 0.5-km vertical resolution has been used to simulate different cases during the first FIRE Cirrus experiment. We are comparing the data from FIRE and the results of model simulations that use different cloud parameterizations: a prognostic, size-dependent cloud scheme developed at Ames Research Center; a bulk-water prognostic scheme; and a semiprognostic, relative-humidity-dependent scheme.

Molecular-absorption probabilities for selected temperature and pressure combinations are being calculated for selected spectral regions for eventual representation in the form of a look-up table. For applications with smaller accuracy requirements, different gaussian quadrature representations of the absorption probabilities are also being calculated. The accuracies of the probability function and its various quadrature approximations are currently tested by comparing their absorption to those from line-by-line data.

We have constructed detailed microphysical models for both marine stratus and cirrus clouds and are currently using these models to reproduce data obtained in field programs. We have successfully duplicated turbulent transport, microphysical, and radiation measurements made by Nicholls in buoyancy and shear-driven marine stratus. We are comparing the cirrus model results with data from the FIRE Cirrus program.

DEVELOPMENT OF PRECISION INFRARED RADIOMETERS FOR THE ARM PROGRAM

VALERO, FRANCISCO P. J.

NASA AMES RESEARCH CENTER

FY 1991	226
FY 1990	0
FY 1989	0

10/01/91-09/30/92

Objective. To develop state-of-the-art infrared radiometric instrumentation for precise measurements of terrestrial and atmospheric infrared fluxes and radiances.

Product. Two electrically calibrated pyroelectric radiometers capable of precise measurements of infrared sky radiance or downwelling infrared flux over a narrow spectral interval between 8 and 12 microns.

Approach. Two instruments [a narrow spectral bandpass, narrow field of view multiple spectral channel infrared radiation radiometer (NFOVR) and a hemispherical field of view, multiple spectral channel infrared flux radiometer (HFOVR)] will be designed, and prototypes will be built. Design and assemble A computer-based control and data-acquisition system will be designed and assembled so they are dedicated to the two instruments and consistent with CART data system requirements. Both instruments will be integrated with control and data acquisition systems and laboratory tested. Instrumentation will be modified as necessary to achieve performance objectives. All prototype instrumentation will be delivered to the ARM CART site for field evaluations.

INFRARED SPECTROSCOPY RELEVANT TO THE ARM PROGRAM

VARANASI, PRASAD

LOS ALAMOS NATIONAL LABORATORY
and STATE UNIVERSITY OF NEW YORK
AT STONY BROOK

FY 1991	475
FY 1990	0
FY 1989	0

10/01/91-09/30/92

Objective. To investigate the infrared-absorption properties of atmospheric greenhouse gases, especially water vapor, to contribute to better estimates of the atmospheric absorption of solar and terrestrial radiation.

Product. High-spectral-resolution data on the absorption coefficients of selected atmospheric trace gases that may contribute to greenhouse warming.

Approach. Laboratory experiments will be performed with a state-of-the-art infrared Fourier transform spectrometer and cryogenically cooled absorption cells. Infrared spectroscopic parameters of several atmospheric trace gases, particularly water vapor, will be determined for ranges of temperature and pressure representative of crucial regions of the atmosphere.

Of particular interest is the water-vapor-continuum absorption band. High-quality spectroscopic data is needed to identify the physical processes that account for this feature of the atmosphere's IR-absorption spectrum. Once the mechanisms are established, we will develop more-reliable models for the role of the continuum in the real atmosphere, where the changing profiles of the important parameters of temperature, pressure, humidity, clouds, and aerosols are complex.

LOCAL DATA MANAGEMENT FOR THE ARM INITIATIVE

VITKO, JOHN, JR.

SANDIA NATIONAL LABORATORIES

FY 1991	49
FY 1990	50
FY 1989	0

10/01/90-09/30/91

Objective. To develop guidelines and decision criteria for evaluating ARM onsite data-management systems.

Product. A report describing the local data-management needs, options, and issues and a decision framework for evaluating proposed data-management concepts.

Approach. We will develop a detailed set of system requirements; assess existing and near-term technologies in the related areas of computing hardware and software, data communication, and methodologies for data fusion and quality control; and develop and apply criteria and methodologies for evaluating proposed data-management architectures.

Results to Date. We have contributed to the design of the CART data system general functional requirements through the WISDM, Inc., quality systems design process.

We refined the functional requirements and produced the conceptual design for the model "whole system" of the data system (one of the five subsystems of the CART data system that were formed by grouping the internal functions around interactions with models, data, instruments, experiments, and sites). After our initial work, the model whole system was subsumed by the experiment whole system, and we produced a conceptual design for the expanded experiment whole system.

We modeled the capacity requirements of the computational, communications, and storage components of the experiment control center, based on the current measurement requirements of the four general measurement strategies and with the flexibility to accommodate future requirements.

We evaluated distributed visual programming languages (DVPLs) for use in model encapsulation and in experiment design and control. The features of these DVPLs will be explored further to define the requirements of the experiment control center.

TREATMENT OF CLOUD RADIATIVE EFFECTS IN GENERAL-CIRCULATION MODELS

WANG, WEI-CHYUNG

STATE UNIVERSITY OF NEW YORK AT ALBANY

FY 1991	349
FY 1990	328
FY 1989	0

09/15/91-09/14/92

Objective. To improve the parameterizations in current GCMs of the radiative effects of clouds' vertical overlapping, to incorporate the cloud optical properties into radiation codes, and to evaluate effects of these improvements on climate simulations.

Product. Improved large-scale atmospheric models, evaluation of parameterizations of clouds and radiative-transfer processes, and specification of measurements and parameterizations that might substantially improve their performance.

Approach. The effects of clouds' overlapping horizontally at different heights and variations in their optical properties will be investigated with the use of ground- and satellite-based measurements. The adequacy of random cloud overlapping, currently assumed in all GCMs, will be evaluated by comparison of results to those from alternative overlapping schemes that might be more realistic. The cloud optical parameters of single-scattering albedo, the asymmetry factor, and extinction coefficient as a function of wavelength will be precalculated by cloud-particle models for use in GCMs or will be derived from observations from satellites. Radiation codes in large-scale models will then be modified to use these cloud optical parameters.

The new treatments of clouds will be used in simulations carried out with a 1-D radiative-convective model and a 2-D radiative-dynamical model to evaluate the greenhouse effect caused by increasing CO_2, CH_4, N_2O, and CFCs on the present climate. Simulations with the Community Climate Model (CCM) will be carried out in a similar manner. In addition, the CCM will simulate energy balances at ARM testbed sites and in regions expected to have atmospheric radiative balances quite different from those at the ARM sites.

Results to Date. Two studies have been conducted, the model-to-observation comparison of the radiation-cloud treatment in the CCM and the CCM1 experiments of the radiation-cloud-climate interactions associated with the greenhouse gases.

For the first study, we used the observed temperature, humidity, cloud cover, and height at Albany, New York, in December 1986 and July 1987 as inputs to the CCM radiative code to calculate the direct and diffuse solar radiation reaching the surface for both clear- and cloudy-sky conditions. For clear sky, the calculated fluxes are in good agreement with the observations. However, these fluxes are sensitive to total-column O_3 and, to a lesser extent, to surface reflectivity. We plan to replace the zonal mean O_3 values in CCM with TOMS data. For cloudy sky, large differences are found, mainly because of the model's internally assigned cloud

albedo (the lack of interactive cloud optical properties) and to the inadequate cloud vertical overlapping information; the latter may be provided by a combination of the satellite AVHHR data together with the ground-based information.

For the second study, we used the CCM1 to study the differences in the radiative forcing of CO_2, CH_4, N_2O, and CFCs and their implications for climatic effect. The results suggest that the radiation-dynamic interaction through clouds plays a dominant role in causing the differences in regional climate.

ARM SCIENCE AND INSTRUMENT DEVELOPMENT

WESELY, MARVIN L.

ARGONNE NATIONAL LABORATORY

FY 1991	309
FY 1990	450
FY 1989	0

10/01/90-09/30/91

Objective. To assist the rapid improvement in the performance of general-circulation models (GCMs) in predicting global and regional climate.

Product. Coordination of ARM infrastructure activities concerning instrumentation; the identification and installation of observation systems necessary to meet the requirements for data to test numeric-model components being developed for use in GCMs; and coordination of ARM infrastructure activities to establish and operate the first ARM field site.

Approach. Argonne National Laboratory will lead an interlaboratory instrument team whose tasks will be to identify and evaluate technologies for possible incorporation in Clouds and Radiation Testbed (CART) observation systems; to develop the initial operational and calibration protocols for each item of the experimental equipment before transferring it to individual ARM site operators; and to provide technical information to support the acquisition of instruments for ARM sites and the ARM mobile system. In addition, Argonne will provide the site program manager for the first ARM/CART site and will arrange its operation.

Results to Date. A planning session on instrument-selection procedures was held with representatives from the ARM instrument team, project office, science team, instrument development program, site selection and campaigns team, and operations team. These procedures have been documented and partially implemented to select an initial complement of instruments at the first ARM/CART site. These procedures have been reviewed by the ARM management, functional, and science teams.

The initial instrument complement emphasizes observations made at a land surface and includes surface-flux stations to observe air-surface exchange of moisture, heat, and momentum; balloon-borne sounding systems to obtain vertical profiles of wind speed, temperature, and humidity; microwave radiometers to observe vertical integrated columnar amounts of water vapor and liquid; and radar wind-profiler systems coupled with acoustic systems to observe vertical profiles of mean wind-velocity components and temperature.

The instrument team and the operations teams have worked together to propose various methods of deploying the planned surface observational systems. In addition, the site program manager for the first site began activities to determine likely locations for the field installations and to screen these locations with regard to NEPA constraints.

PHOTOMETRIC STUDIES OF CLOUDS FROM AN ARM SITE

WHITEMAN, CHARLES D.

PACIFIC NORTHWEST LABORATORY

FY 1991	150
FY 1990	0
FY 1989	0

11/01/90-09/30/91

Objective. To provide vertical profiles of radiative fluxes through the atmospheric boundary layer to depths of up to 1.5 km to supplement ground-based and aircraft-based measurements.

Product. Routine, inexpensive, vertical, broadband radiometric profiles through the atmosphere under cloudy and uncloudy conditions.

Approach. The system will be comprised of three subsystems: a self-leveling radiometer mounting platform initially carrying a net pyrradiometer, a modified commercial tethered balloon system capable of collecting supplementary vertical profiles of basic meteorological data, and a radio communication link to transmit the radiometric and associated data to the ground station.

During the initial design, theoretical calculations of the effects of the balloon on radiation measurements and the effect of nonlevel radiometers will be performed. A working prototype radiometer profiler will then be designed and fabricated. Very light materials and refined packaging will be used to achieve a low-weight, high-reliability flyable package. The radio communication link to transmit radiometric and associated data to the ground will be developed. Profiler data will be acquired and compared with data from instruments located on a 300-m tower at the Boulder Atmospheric Observatory. The profiler will then be deployed at a CART site, and routine sounding procedures will be developed that can be used by inexperienced operators.

Results to Date. A theoretical model of the performance of tilted radiometers has been developed and used to refine the engineering design of the sky platform. Additionally, the effect of the balloon on the radiometric signal has been investigated theoretically.

A motion-sensing platform has been developed and flown from the balloon tetherline to determine translational and angular accelerations. Hardware and software have been procured and/or developed to process this data, which is being used in the engineering design of the sky platform.

An initial design of the sky platform has been developed, and most of the components have been received, including a specially designed net pyrradiometer. The sky platform will be leveled with an active control loop and on-board leveling motors. Present efforts are focused on procurement and verification of a suitable level sensor.

THEORETICAL CLOUD RADIATION STUDIES

WISCOMBE, WARREN J.

NASA GODDARD SPACEFLIGHT CENTER

FY 1991	168
FY 1990	44
FY 1989	0

03/01/91-12/31/91

Objective. To develop a 3-D radiation-transfer model and make it available to the ARM community and to learn about the statistical nature of clouds and how to represent them in models.

Product. A 3-D radiation-transfer model.

Approach. Models will be developed based on the fractal nature of clouds for the spatial distribution of cloud optical depths. These models will be constrained by data from FIRE and Landsat and by principles from turbulence theory and cloud physics. As a test of their applicability, they will be applied to cloud types that are not used in the development phase. Thus, while the properties of stratocumulus clouds may be used to develop these models, their statistical accuracy will be tested by comparison to cirrus clouds.

The Goddard 1-D Monte Carlo radiation model will be further developed. An attempt will be made to reduce the computer time requirements for this model and to extend this 1-D model to handle a 2-D checkerboard grid of cloud optical depths in space. With a 2-D field of optical depths, the model will be a 3-D radiative-transfer model that can treat cloud fields that are inhomogeneous in two dimensions.

A 3-D Fourier-transform radiation model will be further developed as an alternative to the Monte Carlo model.

The 3-D radiation model will be used with the cloud-optical-depth model to study the sensitivity of the bulk cloud optical properties (i.e., transmission and reflection) to the optical-depth distribution. These studies will be used to evaluate the adequacy of the current assumptions that 1-D radiative-transfer models can be used to treat the 3-D cloud field within each "pixel" (or grid box in a GCM).

Both of these 3-D radiative-transfer models will be documented and generalized so they can be used by the ARM and CART communities. The two models will also be used with the ARM data to test the extent to which averages of time-series data at a single point can be used to represent spatial averages.

Stochastic radiative transfer will be studied as a shortcut to using a brute-force method (wherein many realizations of different cloud geometries must be calculated) to gather reasonable statistics on cloud radiative properties.

Results to Date. No results reported.

NATIONAL INSTITUTE FOR GLOBAL ENVIRONMENTAL CHANGE

The House Appropriations Subcommittee on Energy and Water established and provided the resources for the National Institute for Global Environmental Change (NIGEC) on September 29, 1989. The purpose was to contribute to the knowledge base of global climate change, the reduction of key scientific uncertainties inherent in the projections of future climate states and the perturbations attributed to man's activities, and to the development of policy options applicable to preparing for plausible climate change. NIGEC's mission is to support the sponsoring agency, DOE, in its challenging tasks within the federal Global Change Research Program and at the same time, giving significant emphasis to educational needs by nurturing young scientists specially trained for global environmental change research.

NIGEC has adopted the following balance to its academic research program: research on the scientific aspects of global environmental change (70%), research undergirding the development of policy strategies and options (25%), and educational efforts (5%). The policy-related work seeks the practical application of science in the pursuit of appropriate management of plausible climatic conditions of the 21st century.

From the fall of 1989 until April 1990, the activities focused on the organization of the Institute, the creation of the four regional centers and their directorships at Harvard, Indiana University, Tulane, and the University of California, and the development and review of the proposed research for the first year's funding (FY 1990). The formal proposal for the Institute (with headquarters at University of California, Davis) and the start-up research program was approved by the DOE in April 1990. The formal Cooperative Agreement between the DOE and the University of California-Davis was completed in September 1990.

Each regional center has adopted research thrusts to promote synergism between related projects, to focus on significant global-change features of their geographical region, and to provide integration and applicability of the information obtained. These integrating thrusts add an element of uniqueness to the NIGEC program in comparison to investigator-initiated research grants widely dispersed. In many cases, the regional research themes result in field learning centers important for involvement of young scientists and regional outreach. The research thrusts of each of the regional centers of NIGEC are shown below:

Northeastern Regional Center

- Temperate forests, their role in the global carbon cycle, decomposition processes, and their energy balance.
- Studies of past climates and the development of techniques using C4 plants (e.g. corn and maize) for estimating past climatic states over continents.
- Development of a framework for risk assessment of global climate change.

Midwestern Regional Center

- Atmospheric trace gases, their trends and spatial variability.

- Water resources, biological productivity, and their relationships to climate (with a regional focus on midwestern wetlands).
- Policy issues related to energy use.

Southern Regional Center

- Modeling of recent and past global climate changes.
- Atmospheric chemistry of greenhouse gases with focus on methane emissions from rice fields and ocean-bed methane hydrates.
- Ocean biochemistry.

Western Regional Center

- Atmospheric and oceanographic modeling of global climate change.
- Variations in concentrations of radiatively and chemically important trace (greenhouse) gases in the atmosphere.
- Ecological consequences of global warming for both managed and natural ecosystems.
- Policy related research and education.

Several characteristics of the first year's research program are worthy of emphasizing:

- The use of research thrusts to promote integration and synergism among investigators within each region of NIGEC.
- The cross-cutting theme of atmospheric chemistry linking the regional centers.
- Initial outreach research in the first year wherein at least 20% of each center's funding was to institutions other than the host institution.

In spring of 1991, the four regional centers completed their request for proposal process within their regions to utilize the FY 91 funding. For this fiscal year, the goal is to have 50% of the funding allocated outside of the host institutions. The Coordinating Board of the Institute has authorized the NIGEC Director to utilize a portion of the funds allocated to the institute management entity for especially meritorious endeavors of national significance or uniqueness. Two projects were funded from FY 90 resources. The first is the development of a high school level curriculum on global climate change by the Lawrence Hall of Science, with the curriculum materials being available to the school districts across the country in fall of 1991. This will be an effort of highest quality to provide students with up-to-date information on the planetary issues and challenges of global climate change in the next century.

A second project of unique national interest involves funding the proof-of-concept of first generation unmanned aircraft capable of probing the lower and middle stratosphere to heights of 100,000 feet or more for making measurements of chemical constituents, chemical processes, and radiation fluxes. The funding will result in early test flights in the arctic this June with early data shared with the scientific community. It is expected that this unmanned aircraft capability, wherein the aircraft are retrievable and reusable, will lead to early and economical data on global environmental change and its detailed processes far in advance of data from NASA's Earth Observing System. The particular aircraft being supported is the PERSEUS A being developed by Aurora Flight Services of Alexandria, Virginia.

The Institute is also planning an international conference on the cycling of methane in the atmosphere, and the development of information regarding its sources and sinks. Methane is known to be one of the most important of the greenhouse gases; but with a relatively short residence time in the atmosphere. With only a 10% excess of source over sinks, methane is an important target for atmospheric concentration stabilization. It may in fact be feasible to stabilize methane earlier than carbon dioxide through preventing leakage from natural gas transmission systems, altering diets of ruminants, and changing practices of cultivating rice, for example. The scientific basis of these and other options need development beyond the perception that they may well be a most promising avenue of endeavor. Current research

in three of the regional centers bears on developing information essential for these options. The NIGEC Methane Conference is scheduled for January 4-10, 1992, with Professor F. Sherwood Rowland serving as the Chair.

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Astracts

Northeastern Regional Center

ISOTOPIC COMPOSITION OF ATMOSPHERIC CO_2 FROM PLANT PROXIES FOR HISTORICAL TIMES

McELROY, M. B., and MARINO, B.

HARVARD UNIVERSITY

Research is focusing on high-resolution studies designed to document changes in carbon cycling and in regional temperatures from the pre-industrial era to the present. We also propose to characterize the carbon isotopic composition of CO_2 cycled in the Harvard Forest, complementing ecosystem studies already in place. Data from these interdisciplinary studies should allow unique insights into the extent to which human activity has perturbed these cycles outside of their recent historical ranges.

REGIONAL TEMPERATURES FROM NOBLE GASES IN RELICIT GROUNDWATERS

BROECKER, W. S.; SCHLOSSER, P.; and STUTE, M.

COLUMBIA UNIVERSITY

This research entails analysis of noble gases dissolved in groundwater to infer continental surface temperatures on a range of time scales. This will be coordinated with isotopic studies of archival plant material under the McElroy/Marino project to gain information on the accuracy of various proxies in use for atmospheric CO_2 and temperature.

TURBULENCE AND TURBULENT EXCHANGE AT HARVARD FOREST

FITZJARRALD, D. R., and MOORE, K.

STATE UNIVERSITY OF NEW YORK AT ALBANY

Measurements to define the influence of the forest on surface roughness and surface budgets and fluxes of heat and H_2O will be carried out in all seasons of the year. This activity also provides independent checks on the data quality in the flux measurement program 1. Fitzjarrald and Moore bring expertise and well-calibrated independent instruments providing data suitable for intercomparison with the Harvard group.

SOIL CHEMISTRY AND THROUGHFALL AT HARVARD FOREST

ABER, J. D.

UNIVERSITY OF NEW HAMPSHIRE

Aber and co-workers will perform the soil chemistry part of the experiment discussed under project [illegible] analyzing each plot for

nitrogen nutrient concentrations and mineralization rates. He is also measuring throughfall to help determine the fate of NO_x deposited on the forest.

THE FATE OF ATMOSPHERIC SO_2 USING COSMOGENIC ^{35}S

TUREKIAN, K. K.; TANAKA, N.; and GRAUSTEIN, W. C.

YALE UNIVERSITY

Measurements of sulfur gases and aerosols, including the abundance of the cosmogenic radioactive ^{35}S in each species, will provide unique information on the atmospheric transformation rates of sulfur emitted from northeastern sites. Sulfate aerosols provide potentially key negative forcing in the climate system.

DIRECT MEASUREMENTS OF CARBON DIOXIDE AND NITROGEN OXIDE FLUXES IN CENTRAL NEW ENGLAND

WOFSY, S. C.; MUNGER, J. W.; and DAUBE, B. C.

HARVARD UNIVERSITY

The flux and concentration measurements summarized above will be continued for a second year. An automated gas chromatograph will be installed to measure routinely N_2O and chlorofluorocarbon (CFC) concentrations, in collaboration with Dr. James Elkins of the NOAA Climate Monitoring and Dynamic Lab (CMDL, formerly GMCC). Measurements at the station will be tied to the global trace gas measurement network via intercalibration with CMDL. Data from the new GC will allow determination of emission rates for key greenhouse gases, by observation of correlations between these species and concentrations of CO_2, CO, and other species.

CO_2 RISE, NUTRIENT DYNAMICS, AND LITTER DECOMPOSITION IN A DECIDUOUS FOREST ECOSYSTEM: RELATIONSHIP BETWEEN CO_2 LEVELS, TISSUE CHEMISTRY, AND LITTER DECOMPOSITION

BAZZAZ, F. A.

HARVARD UNIVERSITY

As was planned in the previous year, the experiment on tissue chemistry and litter decomposition will be continued for a second year to consider the effects of the age of plants for high and low CO_2 and nutrients. The plants from this year's experiment have been put out of doors in the garden to overwinter. This was done after all leaves fell and the glasshouse temperatures were gradually reduced to near 0°C. Litter chemistry is being assessed in J. M. Melillo's lab. Thus, the plants were dormant before they were taken to the garden. These seedlings will be brought back to the CO_2-controlled glasshouse in April 1991, before bud break. The temperature in the glasshouse will be raised gradually to simulate weather conditions and the seedlings therefore will break bud at the same time as those in the field. The entire experiment as in the first year will be repeated on these second-year seedlings with the procedures outlined above. Detailed characterization will continue on the growth and metabolism of a second, parallel set of seedlings that were harvested after the first year, to determine physiological and morphological changes that occurred in the various treatments.

DECOMPOSITION RATES AND NUTRIENT DYNAMICS IN A TEMPERATE FOREST: EFFECTS OF CO_2 AND NITROGEN ENRICHMENT

MELILLO, J. M.; NADELHOFER, K.; and STEUDLER, P.

YALE UNIVERSITY

The research teams of Bazzaz et al. and Melillo et al. have been working together on a NIGEC-sponsored project to determine the combined effects of varying nitrogen availability and atmospheric CO_2 concentration on leaf litter quality and the effects of changes in leaf litter quality on decomposition and nitrogen availability. We will continue this work by studying decomposition of litter from the first-year seedlings in the lab and in the field, with the field samples left in place up to 2 years. Also, litter from second-year samples will be analyzed for C/N and lignin/N ratios and will be subject to decomposition studies.

Two major studies are intended to complement this work: a soil-warming experiment and an isotope labeling experiment.

SOURCES OF ATMOSPHERIC METHANE IN THE EASTERN UNITED STATES

HARRISS, R. C., and CRILL, P.

UNIVERSITY OF NEW HAMPSHIRE

This study proposes to initiate continuous, high-accuracy measurements of atmospheric methane at the NIGEC tower in Harvard Forest. These methane data will be integrated with ongoing measurements of CO, CO_2, NO_y, and other atmospheric parameters to elucidate relationships between emission sources, land use, and atmospheric transport of methane at a regional scale. Two specific goals of the study are to better define the distribution and temporal characteristics of regional methane sources in the eastern United States and to define, for the first time, a baseline model for atmospheric methane variability at a continental site influenced by a range of upwind land use activities. These data will be critical to future attempts to develop a U.S. national plan for mitigating the greenhouse forcing potential associated with anthropogenic methane emissions, and for devising monitoring strategies for anthropogenic methane emissions.

NITRIC ACID OVER MIDLATITUDE FORESTS

TALBOT, R. W., and KLEMM, O.

UNIVERSITY OF NEW HAMPSHIRE

Vertical distributions of HNO_3 at Harvard Forest will be measured during a series of intensive measurement programs to define the role of this key species in deposition of NO_y. It is thought that this is the main depositing species, and that the rate of fixed-N input to systems like Harvard Forest is regulated by the rate of its formation in the atmosphere. This hypothesis will be tested by careful data collection on the tower, in clean and polluted air, and in cold and warm seasons. The method to be used (mist chamber) has recently emerged as the most reliable for this measurement.

THE LAYOUT OF RISK ASSESSMENTS AND UNDERSTANDING OF UNCERTAINTIES BY ANALOGY

WILSON, R.; FAJER, E.;
and SHLYAKHTER, A.

HARVARD UNIVERSITY

Simplified parametrizations of the risk factors lead to a factorized form of the result and enable a first attempt to be made at estimating the uncertainties. This is similar to chemical carcinogens where the risk can be approximately separated into four factors. In considering the risks of global warming, there are also several factors in the final calculation, and hence several different sources of uncertainty. These uncertainties must be combined in some way to derive the final uncertainty. For example, if the problem of interest is the rise of the sea level, then there are at least three factors for each of which we should specify a distribution and not merely a single value. Firstly, the emissions; secondly, the factor by which the concentrations relate to emissions. Thirdly, the relation between global temperature and concentrations, and

finally the way in which sea level rise relates to global temperature. By means of the chemical and other analogies, we hope to gain insight on the way risk might be viewed.

ON THE ELICITATION AND COMBINATION OF EXPERT OPINION REGARDING GLOBAL SEA-LEVEL RISE

SOLOW, A. R., and BROADUS, J. M.

WOODS HOLE OCEANOGRAPHIC INSTITUTION

Decisions about responding to global climate change will have to be made in the face of substantial uncertainty. One approach to decision-making under uncertainty is based on Bayesian decision theory. To apply Bayesian decision theory, it is necessary to specify a current probability distribution for uncertain quantities of interest (e.g., model parameters). It is a tenet of the Bayesian approach that information about this distribution resides in the opinions of experts. The research described in this proposal examines two issues in the development of current distributions: the elicitation of the current distribution from a single expert and the combination of the current distributions of several experts into a single current distribution. For concreteness, we will explore these issues in the context of developing a current distribution for future mean global sea level.

DECISION MAKING IN COASTAL AREAS UNDERGOING UNCERTAIN ENVIRONMENTAL CHANGE

BOSTROM, A.; DOWLATABADI, H.; FISCHOFF, B.; MORGAN, G.; PATWARDHAN, A.; and SMALL, M.

CARNEGIE-MELLON UNIVERSITY

Future plans for the development, abandonment, or active protection of coastal areas will depend heavily on the expectations of impending sea-level rise held by residents, builders, zoning agencies and government officials. Uncertainty about and perceptions of future sea-level rise and the resulting potential for damage are key elements in the decision-making process. The proposed task will investigate the impact of uncertainty in sea-level rise on coastal development decisions, the effectiveness of alternative strategies given current levels of uncertainty, and the potential impact on decision making of reductions in the uncertainty of sea-level projections which could result from more aggressive scientific research and data collection efforts. The project will combine a simulation approach for determining the time evolution of future sea-level and storm-damage outcomes, a decision-analytic evaluation of coastal-development decisions, alternative decision rules, and a mental models study of lay perceptions of coastal environmental change. The project will result in information useful in the evaluation of coastal-management policies. Effective communication of this information is dependent on communicators understanding the mental models of their audience.

HOW CLOSE IS CLOSE ENOUGH?

FIERING, M. B.; ROGERS, P. P.; and SOLOW, A.

HARVARD UNIVERSITY

We propose to explore the question of how to assess multidimensional distributed parameter models in terms of the economic and social costs associated with making decisions based on their output. Our aim is to develop approaches and guidelines for accepting or rejecting such models; these approaches and guidelines will be more appropriate than the conventional statistical tests of goodness-of-fit. Regret analysis involves choosing a policy which will minimize some function of the distribution of costs associated with choosing the wrong model. Using regret analysis, we will examine how close a model should be to ground truth in order to reasonably base expensive, long-term, and

potentially irreversible policy decisions on its results. A case study using a few of the widely cited GCM's will help illustrate the methodology of the project. The result of this study will be to develop a Bayesian decision framework for deciding whether a model is close enough to ground truth?

UNCERTAINTY, SIGNALS, AND PUBLIC PERCEPTIONS OF CLIMATE CHANGE

KASPERSON, J. X.; KASPERSON, R. E.; PETERS, H. P.; and RENN, O.

CLARK UNIVERSITY

Building upon earlier work on the social amplification of risk, the research team will explore the role of risk signals in the formation of group and individual perceptions of the risks and uncertainties associated with global climate change. The presence and use of risk signals in the media and the concomitant effect on public perception will receive particular attention. This in-depth analysis will focus on "signal streams" for two specific types of global climate change, global warming and sea-level rise, which have only recently registered as dominant public concerns. The project will also examine the interactions of risk signals with other variables that influence the perception of risk.

Thus the research will entail a clear conceptualization, identification of criteria and classification of risk signals. The research plan includes four specific tasks: validation of a working definition of risk signals, development of a classification of risk signals, identification and evaluation of risk signals in media coverage of global climate change, and analysis of how risk signals affect public perception of the severity and manageability of the risks associated with global warming and sea-level rise. Taken together, these tasks offer a new analytical approach to the study of risk perception.

Midwestern Regional Center

EFFECTS OF ENVIRONMENTAL FACTORS ON PHYTOPLANKTON EMISSIONS OF DIMETHYL SULFIDE: IMPLICATIONS FOR CLIMATE CHANGE

BIRKS, JOHN W.

INSTITUTE FOR RESEARCH IN ENVIRONMENTAL SCIENCE, UNIVERSITY OF COLORADO

This research will investigate the effects of temperature, light intensity, wavelength distribution, and nutrient availability on photosynthesis, dimethysulfonium propionate production, and dimethyl sulfide release from phytoplankton cells. This research will test the hypothesis that phytoplankton in the Earth's oceans provide a negative feedback mechanism for stabilization of climate by emitting dimethyl sulfide in response to increased temperature and/or sunlight intensity.

ISOTOPIC STUDIES OF THE BIOGEOCHEMICAL CYCLE OF CARBON: RELATIONSHIPS BETWEEN pCO_2 AND THE ABUNDANCE OF ^{13}C IN SEDIMENTARY ORGANIC MATTER

HAYES, J. M., and PRATT, L. M.

INDIANA UNIVERSITY

Materials from the water column and sediments of the Santa Monica Basin are being collected and chemically and isotopically (^{13}C and ^{15}N) analyzed to establish relationships between the abundance and isotopic composition of dissolved

CO_2 and to determine abundances and isotopic compositions of organic compounds synthesized by planktonic organisms. These organic compounds are the precursors of the sedimentary biomarkers that provide a geochemical record of ancient environments. We are gathering data that will allow detailed study of the fates of this primary material, especially the factors important in determining whether it is remineralized or buried.

ATMOSPHERIC CONCENTRATIONS OF TRACE LEVEL ORGANICS: DO ORGANOCHLORINES CONTRIBUTE TO OZONE DEPLETION?

HITES, RONALD A.

INDIANA UNIVERSITY

Because large organochlorides (such as PCBs) might be sources of ozone-destroying stratospheric chlorine, this research will determine the tropospheric residence times of about 50 PCB congeners that cover a wide range of vapor pressures and water solubilities. PCB congener concentrations will be measured daily for 2 to 3 years to get an accurate value of the relative standard deviation of their measured atmospheric concentrations from which the residence times can be calculated.

TRACE GAS FLUXES IN THE U.S. MIDWEST: TEMPORAL DYNAMICS AND BIOSPHERIC FEEDBACKS IN AGRICULTURAL ECOSYSTEMS

ROBERTSON, G. PHILIP; PAUSTIAN, KEITH; and KLUG, MICHAEL J.

W. K. KELLOGG BIOLOGICAL STATION, MICHIGAN STATE UNIVERSITY

An intensive, near-continuous measurement program will be carried out on four major cropping systems of the Midwest, a woody biomass system, and two native plant communities to evaluate the importance of major midwest cropping systems to global increases in atmospheric N_2O, CH_4, and CO_2. This project will evaluate and predict the temporal dynamics of N_2O fluxes and estimate the regional importance of these fluxes; relate CO_2 fluxes from agricultural soils to soil nitrogen status and the size of the active fraction of soil organic matter; and determine the extent to which methane consumption in upland soils is suppressed by agricultural practices. This information will be used to extend existing biogeochemical models that simulate net primary production, soil organic matter dynamics, and hydrologic fluxes.

A FIELD STUDY OF METHANE AND CARBON DIOXIDE FLUXES IN A BOREAL WETLAND ECOSYSTEM: MEASUREMENT AND ANALYSIS

VERMA, SHASHI B., and ULLMAN, FRANK G.

UNIVERSITY OF NEBRASKA

The surface fluxes of methane, carbon dioxide, water vapor, and sensible heat in a boreal wetland ecosystem near Red Lake, Minnesota, will be measured and analyzed. A tower-based micrometeorological eddy correlation technique with tunable diode laser spectroscopy for measuring methane fluxes will be used because it causes the minimum disturbance to the microenvironment being studied and provides areally integrated fluxes. The study will provide crucial information needed for extrapolating the localized flux values found with chambers to the regional-level flux values needed to validate regional-scale models of trace gas fluxes and to develop procedures for the interpretation of satellite sensing of ecosystem processes.

TEMPORAL AND SPATIAL VARIABILITY OF METHANE CYCLING IN WETLAND ECOSYSTEMS OF THE NORTHERN TEMPERATE ZONE

WHITE, JEFFREY R., and NEALSON, KENNETH H.

INDIANA UNIVERSITY and UNIVERSITY OF WISCONSIN

This project will investigate the methane produced in a number of wetland environments over an annual cycle with a special focus on the biogeochemical dynamics of methane cycling within bog ecosystems. Spatial and temporal variability in net flux rates of methane to the atmosphere will be measured with static flux chambers throughout the year, and detailed analyses of a number of physical and chemical parameters that may influence methane production and oxidation in bog ecosystems will be performed. The microbial communities involved in methane cycling will be characterized, and the stable isotopic composition of both evolved methane and methane reservoirs at depth in bog porewaters will be measured.

SIMULATION EXPERIMENTS OF INERTIA IN FOREST RESPONSE TO CLIMATIC WARMING

ARMSTRONG, MARC P., and MALANSON, GEORGE P.

CENTER FOR GLOBAL AND REGIONAL ENVIRONMENTAL RESEARCH, UNIVERSITY OF IOWA

This research will model the potential inertia of forest response to climate change by analyzing the spatial dynamics of forest communities during periods of climate change. A computer model of the dynamic processes of establishment, growth, and death of forest trees in a spatially explicit framework will be used: a modified version of JABOWA-FORET. The research will show how the carbon storage and productivity of forest stands are affected by (1) differences between the fundamental and realized niches of forest tree species and (2) fragmentation, barriers, and corridors in the landscape.

SUPRA-REGIONAL MODELING OF GROUNDWATER RESPONSE TO CLIMATE CHANGE

HAITJEMA, HENK

INDIANA UNIVERSITY

Greenhouse-warming projections for the Great Lakes region suggest that any increase in precipitation would be overwhelmed by evapotranspiration, thus reducing groundwater recharge. To evaluate the degree and distribution of this impact, groundwater flow will be modelled for the northern part of Indiana and adjoining sections of Illinois, Michigan, and Ohio. With traditional numerical approaches, the coarse scale necessary to make modeling practical limits the resolution of both the results and even the type of question that can be addressed. Analytic-element groundwater-modelling techniques and a graphical data preprocessor will be employed to selectively include higher-resolution data sets into the model domain.

GENETIC BASIS FOR VARIATION IN FRESHWATER PHYTOPLANKTON PRODUCTIVITY RELATED TO WATER TEMPERATURE

HOAGLAND, KYLE D.; ERNST, STEPHEN G.; and DENICOLA; DEAN M.

UNIVERSITY OF NEBRASKA AT LINCOLN

This study will investigate changes in freshwater food webs resulting from increases in water temperature. The research will focus on planktonic diatoms, the major algal component

in many freshwater and marine ecosystems. The genetic variability of 180 clonal isolates of the cosmopolitan filamentous diatom *Fragilaria capucina* from lakes in six midwestern states will be assessed. Optimal growth temperatures will be ascertained to define strain-specific growth preferences. The primary goal of the research will be to provide baseline information on algal genetic variation for future assessments of the long-term impacts of global warming on surface water quality.

CLIMATE AND NORTH AMERICAN PLANT FORMATIONS: ASSOCIATIONS BETWEEN THE WATER BALANCE AND SATELLITE-DERIVED VEGETATION PATTERNS

JELINSKI, DENNIS E., and CARLETON, ANDREW M.

STATE UNIVERSITY OF NEW YORK AT BUFFALO, and INDIANA UNIVERSITY

This project will seek to establish the relationships between known distributions of various North American vegetation types and their respective spectral [i.e., Normalized Difference Vegetation Index (NDVI)] signatures. In it, NDVI for 11 classes of natural vegetation will be evaluated against independent ground-measured estimates of water balance. Daily NDVI values will be formed into monthly composite images that will then be compared site-by-site to water-balance parameters for the concurrent period plus two antecedent periods. Observations will be integrated to produce seasonal and annual patterns of vegetation activity, which will then be compared over a 5-year period that spans a range of climate conditions over North America.

POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE ON MIDWESTERN LAKES: PHYSICS, FISHES, AND PLANKTON

MAGNUSON, JOHN J.

CENTER FOR LIMNOLOGY, UNIVERSITY OF WISCONSIN

The effects on four Wisconsin lakes of a climate change brought about by a doubling of the atmospheric CO_2 concentration will be estimated through simulations of the lakes. The variables studied will include lake physical properties (e.g., temperature dynamics, light penetration, and mixing patterns) and distribution patterns and bioenergetics of plankton and warm-, cool- and coldwater fish. Thermal-habitat availability for fishes will be evaluated based on vertical temperature profiles. Fish growth will be assessed with a fish bioenergetics model that uses both temperature and expected prey availability to determine expected growth rates of fish. With the general model developed with the Wisconsin lake data, physical conditions will be predicted for lakes from Alaska to Florida based on their physical properties.

AMAZONIAN DEFORESTATION AND CARBON CYCLING MANAGEMENT

MORAN, EMILIO F.

INDIANA UNIVERSITY

Two complementary methodologies (GIS and Landsat image analysis) will be used to extend the spatial and time scales of analyses of areas where the role of swidden management and human control over succession may suggest ways in which to accelerate the restoration of deforested areas. This work will examine the biological process of succession in countering the effects of deforestation, especially slash-and-burn land-use change. Understanding forest succession and managed reforestation in Amazonia may

indicate how ecosystem conservation and restoration may be manipulated.

ADAPTATION, MIGRATION, OR EXTINCTION? A STUDY OF THE INFLUENCE OF CLIMATE CHANGE ON THE BIODIVERSITY AND BIOTIC PRODUCTIVITY OF SELECTED BIOMES OF NORTH AMERICA

RANDOLPH, J. C.

INDIANA UNIVERSITY

The effects of climate change on the forest ecosystems of the Great Lakes region will be studied. A geographic information system (GIS) will be loaded with regional-scale climate data; climate-variable values predicted by general-circulation models (GCMs); appropriate nonclimatic, abiotic environmental variables; and appropriate biotic variables. Multivariate statistical techniques will be used to identify and classify ecoclimatic provinces. This ecological-classification model then will be coupled to the climatic predictions of one or more GCMs to project ecosystem shifts. The migration of biotic communities and the occurrence of new assemblages of organisms will be examined in terms of biodiversity and biotic productivity.

BIOLOGICAL HYSTERESIS IN CLIMATE-CHANGE MODELS FOR THE GREAT PLAINS: IMPLICATIONS FOR PRODUCTIVITY AND HYDROLOGIC CYCLES

SEASTEDT, T. R., and OJIMA, D. S.

UNIVERSITY OF COLORADO and COLORADO STATE UNIVERSITY

Existing data bases from Konza Prairie, a tallgrass research site near Manhattan, Kansas, will be used with a previously validated ecosystem model (CENTURY) to predict productivity responses, carbon source and sink responses, evapotranspiration, and leaching and surface losses for Great Plains ecosystems during climate transition. Simulations of climate change and CO_2 enrichment will suggest the magnitude of the hypothesized biological response, the duration of this transition response, and the type(s) of management practice that would induce significant hysteresis effects.

THE INFLUENCE OF CLIMATIC CHANGE ON THE LONG-TERM HYDROLOGIC AND BIOGEOCHEMICAL TRAJECTORIES OF NORTH AMERICAN WATERSHED-LAKE ECOSYSTEMS

WHITEHEAD, DONALD R.; SWEETS, P. ROGER; and WHITE, JEFFREY R.

INDIANA UNIVERSITY

Long cores of lake sediments will be taken and dated with ^{14}C analysis. The pH, alkalinity, dissolved oxygen concentration, and other water-chemistry and morphometric parameters will be reconstructed from diatom transfer functions. Selected long-core intervals will be examined for a full suite of metals. Plant macrofossils will provide information on lake-level changes. The percentages of water and organics of the various size fractions will be determined to assist in analyzing lake-level change. Lake hydrologic modeling will be employed to corroborate both the paleolimnological results and the possible ranges of associated climate variables, such as precipitation/evaporation ratios.

THE EFFECT OF GLOBAL CLIMATE CHANGE ON WETLAND FUNCTION AND DISTRIBUTION AND THE CONSEQUENT LAND-USE AND ECONOMIC CHANGE

WILLARD, DANIEL E.; KRUTILLA, KERRY; and HAITJEMA, HENK

INDIANA UNIVERSITY

This study will evaluate the hydrologic, ecological, and economic effects of climate-

induced changes on the temporal and spatial distribution of water within selected watersheds that now have significant wetland areas. An integrated hydrologic-ecological model will be developed to show how important variables, such as primary productivity, species composition, and zonal extent of wetland area, respond under alternative climate-change scenarios. The literature on cost-benefit analysis and nonmarketed-goods evaluation will be used to tie such biophysical responses to economic consequences. This kind of information could directly assist policy makers who address large-scale environmental change and who require creative, low-cost strategies to meet the nation's need.

A STUDY OF ENERGY POLICY IN THE MIDWESTERN STATES

BAILEY, MARY TIMNEY

UNIVERSITY OF CINCINNATI

This study will document the current state of energy policies in 17 midwestern states, identify the barriers the states face in developing energy policies, and develop model energy policies for the states and local governments. The largest cities in the region will be surveyed to identify current energy-management programs, the needs of local governments for energy-policy initiatives at the state level, and the level of energy-policy expertise available to local governments. And the long-term effectiveness of energy-efficiency projects undertaken in the eighties will be assessed.

Southern Regional Center

IMPACT OF GLOBAL ENVIRONMENTAL CHANGE ON BIODIVERSITY OF MAMMALS IN THE SOUTH-CENTRAL UNITED STATES

CAMERON, GUY N.

UNIVERSITY OF HOUSTON

The effect of global environmental change on the biodiversity of mammals will be studied, with an initial focus on rodents. The relative importance of variation in climate, net primary production, and landscape fragmentation on biodiversity of rodent feeding groups will be determined. The susceptibility of trophic groups to changes in the environment will be assessed by combining life history traits with the sensitivity of their habits. Finally, since climatic change will affect habitat distribution, productivity, quality, and landscape pattern, effects of various changes in temperature and rainfall upon biodiversity of mammals will be analyzed with the use of geographic information systems.

METHANE EMISSIONS FROM NATURAL WETLANDS

BURKE, ROGER A., JR., and WILKINSON, DAN L.

TEXAS A&M UNIVERSITY

This study will refine estimates of the methane flux and isotopic composition from forested wetlands and evaluate the affects of nutrient and water levels and vegetation type on methane flux and isotopic composition in these systems.

PRODUCTION AND SEA-AIR FLUX OF CARBONYL SULFIDE IN THE COASTAL ENVIRONMENT

CUTTER, GREGORY A.

OLD DOMINION UNIVERSITY

The production and fluxes from coastal waters of carbonyl sulfide (COS), the major source of stratospheric sulfate aerosols, will be examined. The seasonal variability of COS concentrations in estuarine and coastal waters will be determined as well as the atmospheric COS concentrations in the marine boundary layer. With these data, sea-air fluxes will be calculated for different seasons to determine the seasonal variability of COS concentrations in the porewaters of estuarine and coastal sediments and thereby to calculate diffusional fluxes to the overlying water column.

CLIMATE SENSITIVITY, PALEOCLIMATES, AND CLIMATE-MODEL VERIFICATION/CALIBRATION: A PILOT STUDY

HOFFERT, MARTIN I., and
RAMPINO, MICHAEL R.

NEW YORK UNIVERSITY

Climate models will be verified and calibrated with paleoclimate data with the goal of narrowing the range of uncertainty in climate sensitivity to changes in radiative forcing. This goal will be accomplished by assembling and transforming the results of existing paleoclimate studies into formats suitable for climate-model verification and calibration, running general-circulation models with paleoclimatic boundary and initial conditions for specific time slices, comparing the results with paleoclimate data, and using the paleoclimate information to calibrate energy-balance models for three time-slices: the Mid-Holocene (5,000 to 6,000 years ago), the Late Glacial Maximum (~18,000 years ago), and the Last Interglacial Maximum (Eemian; ~125,000 years ago).

RECENT CLIMATIC VARIATIONS AND THE GREENHOUSE GAS—CLIMATE SIGNAL: DETECTING CLIMATIC CHANGE

WATTS, ROBERT G.

TULANE UNIVERSITY

Zero-, one-, and two-dimensional diffusive energy-balance climate models of the atmosphere will be used with one-, two-, and three-dimensional diffusive/advective ocean models to study the effect of the ocean on climate, especially in recent times. Hoffert's paleodata will be used to verify and calibrate the model to narrow its range of uncertainty. Areas of focus will include the distribution of thermal energy in the ocean, the oceanic component of heat transport, the transient response caused by ocean thermal inertia, and possible oceanic forcing.

PHOTOCHEMISTRY RELEVANT TO OZONE DEPLETION AND GLOBAL WARMING

KOPLITZ, BRENT

TULANE UNIVERSITY

The photochemistry of CFC alternatives, such as HFC-134a (CH_2FCF_3) and HCFC-124 ($CHClFCF_3$), will be investigated to find out what conditions, if any, lead to hydrogen-atom production. Earlier work on CCl_3CH_3 photolysis has demonstrated that H atoms can be produced photolytically and that the combination of the H atom with O_3, O_2, or N_2 is an important process in both the lower and the upper atmosphere. In addition to destroying ozone, reactions of this type also convert nongreenhouse gases into greenhouse gases.

FORMATION AND EMISSION OF METHANE IN RICE SOILS: EXPERIMENTAL DETERMINATION AND MODELING ANALYSIS

LAW, VICTOR J.; O'CONNOR, KIM C.; PATRICK, WILLIAM H., JR.; LINDAU, C. W.; and DELAUNE, R. D.

TULANE UNIVERSITY and LOUISIANA STATE UNIVERSITY

This project will determine the CH_4 emission rates from a flooded rice field after application of three levels of urea-N fertilizer. Early data gathered at the Crowley, La., experimental rice farm indicate a significant increase in CH_4 emission with increased urea-N application. The experimental efforts at several locations will be subjected to modeling analysis to more fully understand and extend the experimental results.

ESTIMATION OF CLIMATE SENSITIVITY

NORTH, GERALD R.

TEXAS A&M UNIVERSITY

The climate group at Texas A&M will conduct and analyze several runs of the NCAR Community Climate Model. The model will be applied to an idealized planet and will compare the atmosphere in disturbed and undisturbed conditions. This effort will relate the statistics of the undisturbed run to aspects of the climate's sensitivity to external forcing by testing an important theorem in statistical mechanics known as the fluctuation-dissipation relation.

MODELING PATTERNS OF CO_2 FLUX FROM FOREST ECOSYSTEMS: IMPLICATIONS OF CLIMATE CHANGE

SMITH, T. M.; SHUGART, H. H.; and BONAN, G. B.

UNIVERSITY OF VIRGINIA

An approach for combining an individual-based forest-gap model with a physiology-based model of carbon flux operating at the level of the forest stand will be developed and tested. The combined model will be used to simulate patterns of forest structure and carbon flux at a series of sites representing boreal to subtropical/tropical forests. Patterns will be explored under both current-climate and climate-change scenarios based on general-circulation models.

GLOBAL-WARMING EFFECTS ON THE RELEASE OF LIGHT HYDROCARBONS FROM GAS HYDRATE DEPOSITS

SCHWARZ, STEPHEN G., and JOHN, VIJAY T.

TULANE UNIVERSITY

The amount of light hydrocarbons that global warming could release to the atmosphere from Arctic gas hydrate deposits (crystalline inclusions of water and trapped light hydrocarbons formed under thermodynamic conditions of low temperature and high pressure) will be estimated. Models will be developed that will assess the relative potential of this methane source based on an estimate of the reserves in the region and on the severity of the temperature anomaly.

TRACE-GAS EXCHANGE WITH THE ATMOSPHERE FROM GULF COAST AGRICULTURAL WETLANDS

SASS, RONALD L., and FISHER, FRANK M.

RICE UNIVERSITY

Experiments will measure the annual rate of and seasonal changes in the production, oxidation, and emission of atmospheric trace gases from rice fields; characterize the dependence of methane production and emission on rice-plant development; and determine the source, size, spatial and temporal variation in, and rate of use of carbon substrate pools used by methanogenic and methanotropic bacteria.

SAMPLING THE MARINE GAS-HYDRATE RESERVOIR

PAULL, CHARLES K.

UNIVERSITY OF NORTH CAROLINA

In situ properties of continental-margin gas hydrates and their effects on continental-rise prism sediments off the southeastern United States will be investigated with piston cores. Characteristic sediments that either have not been influenced by tectonics, are exposed along the sole of a major slump, or are exposed along the crest of a breached diapir will be sampled. Measurements of the pore-water and solid-phase characteristics will reveal the amount of hydrate that these sediments contain, the effects of the hydrates on the overlying pore waters and sediment properties in the rise, and the role of marine gas hydrates as contributors to the atmospheric methane pool.

Western Regional Center

PARAMETERIZATION OF CONVECTIVE DOWNDRAFTS AND NUMERIC SIMULATION OF GLOBAL HYDROLOGY

ARAKAWA, AKIO, and
MECHOSO, CARLOS R.

UNIVERSITY OF CALIFORNIA AT LOS ANGELES

The effect of cumulus convection on the water-vapor budget will be studied by systematically investigating both the time-dependent and stationary solutions of a revised updraft-downdraft model, improving parameterization of cumulus convection, incorporating the revised version into the UCLA GCM, investigating the impact of downdrafts on subcloud-layer and surface fluxes, simulating global hydrology, and investigating the response of the water-vapor field to warmer surface temperatures.

DESIGN AND INSTALLATION OF A MONITORING STATION FOR ASSESSING THE IMPACT OF ANTHROPOGENIC AEROSOLS ON CLIMATE

CHARLSON, ROBERT J., and
COVERT, DAVID S.

UNIVERSITY OF WASHINGTON

This project will initiate a measurement program aimed at acquiring an observational data base on the direct radiative effect of anthropogenic aerosols. A ground-based aerosol-monitoring station will be designed, fabricated, installed, and tested. A network of four midlatitude stations will then be deployed to provide aerosol data documenting inter- and intrahemispheric differences caused by industrial activity.

SEARCH FOR MARINE SOURCES OF ATMOSPHERIC METHYL HALIDES

CICERONE, RALPH J., and
LIDSTROM, MARY E.

UNIVERSITY OF CALIFORNIA AT IRVINE and CALIFORNIA INSTITUTE OF TECHNOLOGY

This research will develop improved methods of analysis for the methyl halides (CH_3Cl, CH_3Br, and CH_3) and conduct several seawater-sampling campaigns in near-coastal waters to measure gas amounts and spatial and temporal variations. These campaigns will take regular measurements in marine and continental air and in seawater to determine the size of the marine source of these gases, which are important in atmospheric chemistry because they are sources of chlorine and bromine for the stratosphere. The amounts

of methyl halides released from laboratory phytoplankton cultures under controlled conditions will also be measured.

EMPIRICAL MODEL FOR THE EFFECT OF CLOUDS ON THE EARTH'S RADIATION BUDGET

COAKLEY, JAMES A., JR., and LUO, GANG

OREGON STATE UNIVERSITY

Spatial coherence and bispectral retrievals will be applied to NOAA Advanced Very High Resolution Radiometer imagery data to characterize the radiative properties of marine stratocumulus. Reflectivities will be used to estimate liquid water paths for both uniform and broken cloud systems. Frequency distributions will be obtained for the liquid water paths, the fractional cloud cover, and the joint distribution of liquid water path and fractional cloud cover. The sensitivity of the results to droplet size will be explored.

INTERACTIVE VEGETATION FOR CLIMATE MODELS OVER THE SEASONAL CYCLE

DICKINSON, ROBERT E., and GRAUMLICH, LISA J.

UNIVERSITY OF ARIZONA

The modeling of water and carbon fluxes at the land surface will be improved by developing a seasonally interactive treatment for leaf carbon. The new treatment will be tested by integration in the NCAR Community Climate Model and by comparison of the carbon cycle results against current estimates of net primary productivity. Sensitivity studies will address the dependencies on key model parameters. The leaf carbon module will be tested for four model ecosystems as to its ability to predict carbon allocation and net primary productivity.

CRITICAL UNCERTAINTIES IN THE LINKS BETWEEN GLOBAL ENVIRONMENTAL CHANGE AND REGIONAL EFFECTS: IMPLICATIONS FOR POLICIES AFFECTING THE WESTERN U.S.

GOLDMAN, M.; McKONE, T. E.; DANIELS, J. I.; and ANSPAUGH, L. R.

UNIVERSITY OF CALIFORNIA AT DAVIS and LAWRENCE LIVERMORE NATIONAL LABORATORY

This project will develop a matrix that links global environmental change with regional effects (direct, indirect, and interactive) in the western United States; characterize the magnitude and uncertainty of these effects; identify the critical uncertainties in the predictions of these effects, their interactions, and their potential influence on the regional economy; and translate them into terms that can be understood and used by policy makers to formulate strategies.

IMPACTS OF GLOBAL WARMING ON THE HYDROLOGY AND AQUATIC ENVIRONMENT OF A MESOSCALE GEOGRAPHICAL REGION

KAVVAS, M. L., and ORLOB, G. T.

UNIVERSITY OF CALIFORNIA AT DAVIS

This research project will bridge the gap between the spatial scales of general circulation models (GCMs) and those of hydrology and water-quality models. It will then couple an in-house mesoscale atmospheric model (MAM) with the GCM of the Geophysical Fluid Dynamics Laboratory. It will also develop a physics-based hydrology model at small mesoscale. Output from the MAM for a particular climate-change scenario will then be input to the hydrology model for specified geographic areas to determine the impact of the particular climate-change scenario on the region's hydrology.

DEVELOPMENT OF A GAS-TO-PARTICLE CONVERSION MODEL FOR USE IN 3-D GLOBAL SULFUR BUDGET STUDIES

KREIDENWEIS, SONIA M.

SAN JOSE STATE UNIVERSITY

To study the global sulfur budget, a model will be developed that incorporates major sources of particles and precursor gases and that describes the conversion of gases to particulate matter. Model predictions will be compared with available measurements of the size and number distribution of aerosols in various regions of the globe. The relative influences of continental and oceanic sources of sulfur will be investigated with the 3-D model with available emission-source maps.

EFFECTS OF GLOBAL CLIMATE AND ATMOSPHERIC CHANGE ON THE STRUCTURE AND FUNCTION OF MEDITERRANEAN SHRUB ECOSYSTEMS AND ASSOCIATED FOREST ECOTONES IN CALIFORNIA

OECHEL; WALTER C.

SAN DIEGO STATE UNIVERSITY

This project will begin to determine the field-ecosystem responses (e.g., in water use, evapotranspiration, water yield, productivity, species composition, albedo, and fire frequency) of woody and semiarid ecosystems to elevated CO_2. Initial emphasis will be on the response of the chaparral shrublands of the Mediterranean-type climate region of the United States; later work will include woodland and montane forest ecosystems of that region.

GLOBAL STUDIES OF TRACE-GAS CONCENTRATIONS; MEASUREMENT OF THE OXIDATIVE CAPACITY OF THE EARTH'S ATMOSPHERE

ROWLAND, F. SHERWOOD

UNIVERSITY OF CALIFORNIA AT IRVINE

Air samples will be collected at ground level from many cities around the world, and excess CH_4 in urban locations will be correlated with CCl_2F_2 (CFC-12) as a test of the CH_4 source distribution. Worldwide studies will also be made of source strengths of methylchloroform (CH_3CCl_3), carbon monoxide, and low-molecular-weight alkanes. Measurements of urban concentrations of such molecules as $CHCl_3$ and $CCl_2=CCl_2$ will furnish useful comparisons with concentrations in remote regions and will serve as prototypes for the behavior in the atmosphere of the proposed substitutes for the CFCs.

EFFECTS OF GLOBAL WARMING ON CALIFORNIA CLIMATE

SOONG, SU-TZAI; LEE, ROBERT; and DICKERSON, MARVIN H.

UNIVERSITY OF CALIFORNIA AT DAVIS and LAWRENCE LIVERMORE NATIONAL LABORATORY

This project will assess the extent of regional-scale climate change over California and the surrounding states from the increase in greenhouse gases. It will also investigate the physical processes that control climate change with a regional-scale model nested in a general-circulation model (GCM). The project will include data analysis and benchmark studies of two contrasting winter seasons: the wet season of Dec.—Feb. 1982 and the dry season of Dec.—Feb. 1988. The verified model will be used to study the regional-scale climate change caused by 1 x CO_2 and 2 x CO_2 global warming.

ISOTOPICALLY LABELED CO_2 FROM THE STRATOSPHERE: A TRACER OF CARBON BIOGEOCHEMISTRY

YUNG, YUK L., and THIEMENS, MARK H.

CALIFORNIA INSTITUTE OF TECHNOLOGY and UNIVERSITY OF CALIFORNIA AT SAN DIEGO

This study of isotopically enriched $CO^{18}O$ and $CO^{17}O$ in the atmosphere will focus on the chemical kinetics of oxygen exchange between CO_2 and O_3 via the excited radical $O(1d)$. The laboratory results and atmospheric measurements will be used to model sources and sinks of CO_2 isotopomers in the stratosphere and troposphere.

MODELING ANALYSES OF METHANE EMISSIONS FROM RUMINANTS

R. L. BALDWIN

UNIVERSITY OF CALIFORNIA AT DAVIS

A generally validated, mechanistic, dynamic model of ruminant digestion will be used to study methane production by ruminants. Studies of feeding and management strategies used in the U.S. beef and dairy cattle industries will be extended with estimates of methane emissions and animal census and productivity data to estimate total ruminant methane emissions for the United States and the world. The model will also be interfaced with economic elements to allow cost-benefit analyses of possible interventions directed at reducing methane emissions by ruminants.

ISOTOPIC CHARACTERIZATION OF THE SOURCES OF ATMOSPHERIC NITROUS OXIDE

CRAIG, HARMON, and KIM, KYUNG-RYUL

SCRIPPS INSTITUTION OF OCEANOGRAPHY, UNIVERSITY OF CALIFORNIA AT SAN DIEGO

This research will characterize both the ^{15}N and ^{18}O signatures in N_2O emissions from natural and cultivated soils in tropical and temperate regions. In the course of the research, analytical methods will be developed to isotopically analyze small samples of N_2O with direct mass-spectrometric measurements in addition to the current methods based on the conversion to N_1 and CO_2.

GLOBAL WARMING TRENDS AND INTERNAL CLIMATE OSCILLATIONS: DETECTION AND MODELING

GHIL, MICHAEL, and NEELIN, J. DAVID

INSTITUTE OF GEOPHYSICS AND PLANETARY PHYSICS and UNIVERSITY OF CALIFORNIA AT LOS ANGELES

With singular spectrum analysis, an advanced tool for statistical analysis that uses data-adaptive filters, this study will attempt to decompose the existing multidecadal records of surface temperature, sea-level pressure, and sea-level height into their principal components with respect to spatial and temporal variability and then to relate these statistical features to biogeochemical, physical, and dynamic mechanisms, both natural and anthropogenic. Modeling of interdecadal oscillations based on the extratropical ocean circulation will also be pursued.

INTERACTIVE EFFECTS OF HEAT STRESS AND ELEVATED CARBON DIOXIDE CONCENTRATION ON PLANT REPRODUCTION

HALL, ANTHONY E.

UNIVERSITY OF CALIFORNIA AT RIVERSIDE

This project will screen and breed cowpea genotypes with both high harvest index and heat tolerance and then study the responses of

contrasting cowpea genotypes in open-topped, CO_2-enriched growth chambers. It will determine whether heat-tolerant genotypes are more responsive to elevated CO_2 than present heat-sensitive cultivars under high temperatures, whether genotypes with a high harvest index under present-day conditions are more responsive to CO_2 enrichment, and whether there is a positive genotypic correlation between harvest index and stable-carbon-isotope discrimination.

POSSIBLE INFLUENCE OF CLIMATE CHANGE ON A RECENT INCREASE IN NONINDUSTRIAL CO_2 EMISSIONS TO THE ATMOSPHERE

KEELING, CHARLES D.

SCRIPPS INSTITUTION OF OCEANOGRAPHY, UNIVERSITY OF CALIFORNIA AT SAN DIEGO

This study will examine how the amount of carbon dioxide in the atmosphere and in the carbon cycle is affected by climatic change by determining how atmospheric CO_2 is distributed geographically. Because the $^{13}C/^{12}C$ ratio of atmospheric CO_2 distinguishes the oceanic from the terrestrial feedbacks, measurements of both CO_2 and the $^{13}C/^{12}C$ ratio will allow investigation of the causes of increased releases of vegetative CO_2 to the atmosphere that have been detected. Areas that are the least disturbed by human activities, the tundra of Alaska and the forests of western Canada and the U.S. Pacific Northwest, will be targeted.

PLANT AND ECOSYSTEM RESPIRATION IN A CHANGING CLIMATE: MODELING AND EMPIRICAL STUDIES

MOONEY, HAROLD A., and VITOUSEK, PETER M.

STANFORD UNIVERSITY

The responses of soil-organic-matter (SOM) respiration to clearly defined temperature gradients will be investigated, and an existing ecosystem model will be improved to make its SOM module appropriate for a broader range of vegetation types. These studies will lead to a general respiration model parameterized for grassland, shrubland, and forest ecosystems in coastal central California.

A STUDY OF HYDROLOGIC EXTREMES IN CALIFORNIA

ROADS, JOHN O., and CHEN, S. C.

SCRIPPS INSTITUTION OF OCEANOGRAPHY, UNIVERSITY OF CALIFORNIA AT SAN DIEGO

To be able to predict interannual and longer-term variations in precipitation and ultimately the surface hydrology, the available meteorological record will be examined to determine the characteristic large-scale circulation patterns associated with warm, cool, wet, and dry conditions. Whether the relevant hydrologic patterns and their antecedent evolution can be simulated by a general-circulation model will be determined, and the characteristic small-scale features of such circulations will be described with a fine-mesh model and available station data.

MODELING THE RESPONSE OF THE CALIFORNIA CURRENT SYSTEM TO GLOBAL GREENHOUSE WARMING

SOMERVILLE, RICHARD C. J., and PARES-SIERRA, ALEJANDRO

SCRIPPS INSTITUTION OF OCEANOGRAPHY, UNIVERSITY OF CALIFORNIA AT SAN DIEGO

The response of the California ocean current system to the large-scale forcing thought to be

associated with greenhouse warming will be investigated. Wind-forced ocean-circulation models will be used to investigate the relative importance and possible effects on the regional climate of two mechanisms: (1) the enhancement of coastal upwelling and downwelling by the intensification of the local winds and (2) the effects of remotely (e.g., equatorially) generated warm and cold events propagating into the region in the form of coastal waves.

CORRELATION OF CONTINENTAL AND MARINE PALEOCLIMATE RECORDS BY THE USE OF THE PALEOINTENSITY OF THE GEOMAGNETIC FIELD

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Variations in the paleointensity of the geomagnetic field, as recorded by sequences of lake and marine sediments from the western United States and northeastern Pacific Ocean, will be studied to correlate continental and marine paleoclimate records. Such correlations would allow creation of a common time scale for marine and continental records, permit comparison of climate processes in each environment, and allow verification of computer models of global climate change.

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