Our Changing Planet:
The FY 1990 Research Plan

THE U.S. GLOBAL CHANGE
RESEARCH PROGRAM

A Report by the
Committee on Earth Sciences

July 1989

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A Report by the Committee
on Earth Sciences

July 1989

Office of Science and Technology Policy Federal Coordinating Council on Science, Engineering, and Technology

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(See Appendix C for the CES Charter)

EXECUTIVE OFFICE OF THE PRESIDENT
OFFICE OF SCIENCE AND TECHNOLOGY POLICY
Washington, D.C. 20506

Early in 1989, I transmitted to the U.S. Congress a report which accompanied the President's FY 1990 Budget outlining the goals, implementation strategy, and research budget of the U.S. Global Change Research Program. This strategy document, entitled "Our Changing Planet: A U.S. Strategy for Global Change Research," was the product of an intense interagency effort by experts in various earth sciences and other disciplines. This interagency effort was coordinated by the Committee on Earth Sciences (CES) of the Federal Coordinating Council for Science, Engineering, and Technology. The strategy document promised a detailed and comprehensive research plan based on the research strategy to be published in 1989.

I am pleased to forward with this letter the U.S. Global Change Research Program research plan for FY 1990. This research plan focuses on establishing a sound scientific basis for developing national and international policy on global change issues. Global changes such as desertification, drought, volcanism, and global warming can have a tremendous economic and societal impact. The relative roles of human activity and natural processes in these changes are of great importance but are, at present, unknown. In addition, our knowledge is insufficient to reliably predict the likely degree, rate, or timing of these changes. Improving our ability to understand and to ultimately predict global changes, whether natural or human-induced, is essential. The CES research plan represents a well-coordinated federal research program to address these issues and provides a strong foundation for international cooperation.

The scientific objectives of the research plan are to monitor, understand, and ultimately predict global change. The report outlines a priority framework for focusing and integrating the interagency research efforts to ensure that they meet these objectives. This priority framework was derived from numerous research priorities outlined by both the U.S. and international communities. It indicates research areas that require progress to improve our understanding of both natural and human-induced global changes. This research plan provides a solid foundation for future planning and will be updated periodically to reflect our growing understanding of global environmental changes.

I take this opportunity to thank and commend Chairman Dallas Peck and his interagency committee members and staff who have done an outstanding job in preparing this report.

William R. Graham

William R. Graham
Director

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Preface

In January 1989, a report entitled "*Our Changing Planet: A U.S. Strategy for Global Change Research*" accompanied the President's Fiscal Year 1990 Budget to the Congress. This report drew attention to the significant environmental issues arising from both natural and human-induced changes in the global "Earth system." It underscored the scientific uncertainties and policy challenges that are associated with them. To address these issues and uncertainties, the report announced the beginning of a U.S. research program that will focus on the scientific questions posed by global change. This multi-agency endeavor, the U.S. Global Change Research Program, will seek to improve understanding of the causes, processes, and consequences of the changes affecting our planet. By so doing, the Program may provide a sound scientific basis for related public policy decisions.

The present document, "*Our Changing Planet: The FY 1990 Research Plan,*" describes the beginnings of the Program and sets forth a comprehensive research plan that will be updated annually. It reviews the changes that have occurred in the past, the forces that are at work today, the strengths and weaknesses in our current understanding and research activities regarding global change, and our potential for predicting global change in the future. It identifies research activities and funding levels by the Federal agencies, particularly the Fiscal Year 1990 initiatives and augmentations, that seek to address the gaps in current knowledge. Finally, it outlines the science priorities that must be addressed by the Program in the coming years to gain a better predictive understanding of the global system.

This Research Plan describes the details of the U.S. Global Change Research Program. In addition, an accompanying, comprehensive Executive Summary has been published separately. It provides the highlights of the scientific background, purpose, goals, scope, priorities, and budget of the U.S. Global Change Research Program. A summary of those highlights is presented here.

THE U.S. GLOBAL CHANGE RESEARCH PROGRAM AT-A-GLANCE

- ❑ Many global changes can have tremendous impact on the welfare of humans. These events may stem from natural processes that began millions of years ago or from human influence. Responding to these changes without a strong scientific basis could be futile and very costly.

- ❑ This report presents a comprehensive research plan for the U.S. Global Change Research Program.

- ❑ The goal of the Program is to provide a sound scientific basis for national and international decision making on global change issues.

- ❑ The Program's goals, objectives, research priorities, and strategy are consistent with current national and international global change planning and research efforts.

- ❑ The scientific objectives of the Program are to <u>monitor</u>, <u>understand</u>, and ultimately <u>predict</u> global change.

- ❑ The Program is broad in scope, encompassing the full range of Earth system changes, including physical, chemical, geological, social, and biological changes. The Program addresses both natural phenomena, as well as the effects of human activity.

- ❑ The particular research activities which comprise the U.S. Global Change Research Program are grouped into seven interdisciplinary scientific elements:

  1. Climate and Hydrologic Systems
  2. Biogeochemical Dynamics
  3. Ecological Systems and Dynamics
  4. Earth System History
  5. Human Interactions
  6. Solid Earth Processes
  7. Solar Influences

- ❑ In fiscal year 1989, funding for focused global change research activities total $133.9 million. The President's FY 1990 budget proposes a funding level of $191.5 million, a 43 percent increase for focused programs. This substantial increase will enable the Program to expand and accelerate its research activities in most areas of global change research.

- ❑ This strategy was developed by a U.S. Federal interagency group, the Committee on Earth Sciences of the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET). The FCCSET is chaired by the Director of the Office of Science and Technology Policy in the Executive Office of the President.

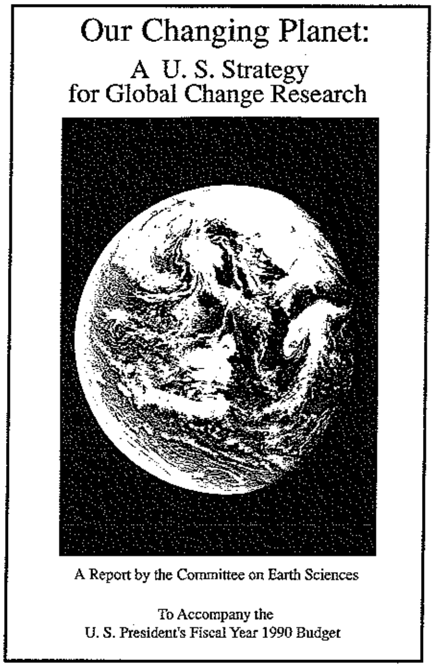
Introduction

Purpose and Structure of This Document

This document is a *comprehensive extension* of the outline of the U.S. Global Change Research Program presented in *Our Changing Planet: A U.S. Strategy for Global Change Research* (Committee on Earth Sciences, January 1989). That brief overview of the Program accompanied the President's Fiscal Year 1990 Budget, the first budget to reflect specific *augmentations* for Government-wide, integrated research focused on global change.

Our Changing Planet: A U.S. Strategy for Global Change Research summarized:

- the manifestations of natural and human-induced global change;
- societal needs for a better scientific understanding of such changes;
- key scientific questions that must be answered;
- the U.S. Global Change Research Program's goals, research objectives, and implementation strategy for addressing those questions;
- agencies and national and international organizations involved; and
- the Fiscal Year 1989 and 1990 budgets, by agency and activities.



This follow-up document sets forth an initial research plan (Plan) for the U.S. Global Change Research Program. *Its purpose is to facilitate the planning and coordination of the Federal research and budgetary activities of the Program.* The Plan has been developed in response to the recent recognition by national and international scientists and policymakers that the global Earth system may be significantly altered as a result of mankind. In formulating the Plan, the Committee on Earth Sciences (CES) has drawn upon the national and international research plans and recommendations developed by the scientific communities over the past few years that call for a systematic and integrated study to better understand the global environment and its susceptibility to change. In particular, the CES has drawn heavily on the work of the Committee on Global Change of the U.S. National Academy of Sciences (CGC/NAS), the World Climate Research Program (WCRP) of the World Meteorological Organization (WMO) and the International Council of Scientific Unions (ICSU), and the International Geosphere-Biosphere Program (IGBP) of ICSU. The Plan has been prepared primarily for those who make decisions regarding the conduct and funding of global change research and related activities, including:

- Federal research agencies
- Federal executive offices
- Congress

Preparation of an annual plan, such as this first one, will aid development of a suite of Federal research agency activities that (i) are closely linked and complementary and (ii) have a common intellectual framework and goal. Together, these activities make up the Program. The Plan will serve as a common platform for describing the proposed U.S. Global Change Research Program budgets of the agencies for each fiscal year. By outlining the key questions, the research needs, and the priorities established, the Plan will be an important aid to the Office of Management and Budget and to Congress in decisions regarding budget allocations.

In addition, by defining the initial research and implementation strategies of the Program, the Plan will be a useful vehicle for the review and advice of the CGC/NAS and other scientific organizations. It will also assist in coordination and planning of the U.S. Global Change Research Program with analogous international endeavors, such as the IGBP and WCRP, and other elements of the World Climate Program (WCP). CES will continue to develop and emphasize a science plan and management structure that involves explicitly both national and international partnerships between scientific and government organizations.

This document has three main sections, as follows:

- "The Program's Approach to Global Change Research" establishes what scientific knowledge is necessary and what is the best current approach to acquiring it *in order to understand global change so that its impacts can be more reliably predicted.* This section:
    - establishes the goal sought and its achievability,
    - poses the scientific questions that must be addressed, and
    - describes the implementation strategy, i.e., the objectives that must be reached, the nature of the interdisciplinary scientific work that must be done, and the organizational structure that must be achieved to make the endeavor efficient.
- "The Research Plan" examines the activities and needs for each of the seven interdisciplinary science elements: climate and hydrologic systems, biogeochemical dynamics, ecological systems and dynamics, Earth system history, human interactions, solid Earth processes, and solar influences. For each of these elements, the document does the following:
    - assesses the strengths of current agency programs,
    - identifies the weaknesses and the highest priority areas of needed research, and
    - outlines FY 1990 research initiatives and/or augmentations by Federal agency.
- "Priority Framework for the U.S. Global Change Research Program" describes how the Program will proceed to meet the proposed objectives. The overall strategic, integrating, and research priorities are summarized. The strategic and integrating priorities that guide the implementation of the program and the research needs that are deemed to be of the highest priority within the program and the seven science elements are outlined. Lastly, the FY 1989 and 1990 U.S. Global Change Research Program budgets are tabulated.

- "FY 1989-1990 U.S. Global Change Research Program Budget" tabulates and presents the budgets for the various research programs by science element, agency, and Federal Budget Function.

Three appendices contain related information and additional supporting details:

- *Appendix A* summarizes the *role* of each of the Federal agencies in the U.S. Global Change Research Program, and

- *Appendix B* defines the terms used in this document, tabulates the FY 1989 and FY 1990 budgets for both the focused and contributing programs, and describes the agencies' FY 1989 global change activities, categorized by the interdisciplinary science elements. The analyses of the strengths and weaknesses of current research found in the main text are drawn from the information in this Appendix.

- *Appendix C* contains the charter for the Committee on Earth Sciences.

This document focuses primarily on the research planning associated with the FY 1990 budget process and also serves as a guide for future planning and development of the Program. The Plan will be updated annually. Each update will document the progress of the Program and highlight its major accomplishments. It must be emphasized that this program description and plan present a description of the current activities and organizational framework and the initial priorities for the U.S. Global Change Research Program. In developing both the Plan and the science priorities, consideration was given to the scientific needs and importance of each activity, budgetary constraints, the maturity of the scientific planning, and the institutional and organizational support required to initiate or augment specific research activities. The Program priorities and emphases certainly will change as scientific understanding, agency infrastructure, and national and international organizational structures evolve. *The degree to which future research requires that these analyses be updated, and hence the degree to which the annual versions of this document change, will be a measure of success of the U.S. Global Change Research Program.*

Background to The U.S. Global Change Research Program

What Is Global Change?

The Earth is a place of change. The geological record testifies that the Earth's environment has been subject to change over eons - much of it occurring slowly over many millennia, but some relatively rapidly over decades. The changes are in response to such phenomena as the migration of continents, the building and erosion of mountains, the reorganization of oceans, the orbital characteristics of the sun and the planets, variations in solar output, and even the catastrophic impacts of large meteorites. These underlying causes lead to changes on local, regional, and global scales: a succession of warm and cool epochs, the appearance and disappearance of large deserts and marshlands, new distributions of tropical forests and rich grasslands, advances and retreats of great ice sheets, rising and falling sea and lake levels, and the extinction of vast numbers of species.

Although *these* changes are the inevitable results of major natural forces beyond human control, it is apparent that a relative newcomer to the scene - *Homo sapiens* - has now become a powerful agent of environmental change. The chemistry of the atmosphere has been altered significantly by agricultural and industrial revolutions. The erosion of continents and sedimentation of rivers and shorelines have been influenced drastically by agriculture and construction. The production and release of toxic chemicals have affected the health and distributions of biotic populations. The development of water resources has affected patterns of natural water exchange in the hydrological cycle (e.g., enhanced evaporation from reservoirs compared to that from unregulated rivers). As world population grows and the world undergoes further technological development, the role of the planet's most influential denizen as an agent of environmental change will undoubtedly expand.

Evidence accumulated in the last two decades indicates that environmental changes are the result of complex interplays among a number of natural and human-related systems. For example, changes in the Earth's climate involve not only winds and clouds in the atmosphere, but also the interactive effects of the biosphere, ocean currents, human influences on atmospheric chemistry, the Earth's orbital characteristics, the reflective properties of the planet, and the distribution of water between the atmosphere, hydrosphere, and cryosphere. Similarly, other important occurrences, such as the productivity of the oceans and land surface or the incidence of volcanic eruptions and earthquakes, are intricately linked to a variety of interactive phenomena. The global aggregate of interactive linkages among the major systems that affect the environment has become defined as Global Change.

Role of Scientific Understanding

Many environmental changes have substantial impact on the welfare of humans: advances and retreats of glaciers, changing lengths of growing seasons, regional land subsidence or uplift, and extreme climatic events such as protracted droughts. During most of mankind's existence, the response to such changes was only to learn to cope: building better shelter, altering agricultural practices, or migrating.

However, advances in the Earth sciences over the last several decades have revealed (i) the causes of some changes, (ii) the processes whereby they occur, and (iii) their local environmental consequences. As a result, rather than having to simply endure unsuspected changes as they occur, people can now anticipate many of them and make decisions and responses that could reduce the impacts.

Thus, science has sought to develop an increasingly improved *predictive understanding* of environmental changes that relate to human welfare. The makers of public policy have sought to use that understanding as part of the basis for decisions that are aimed at lessening the adverse effects of those changes. This ability to predict has two types of applications:

- *natural changes* — better choices in accommodating the unavoidable (e.g., the 1982-1983 "El Niño"), and
- *human-induced changes* — better decisions to ameliorate the consequences of the avoidable (e.g., the 1987 Montreal Protocol related to the protection of the ozone layer).

In both cases, failing to take prudent action leads to adverse impacts; correspondingly, there are adverse impacts of taking imprudent action. The ability to assess the trustworthiness of the prediction is as important as the ability to make the prediction. As a result, a meaningful estimate of the uncertainty of a prediction is a necessary part of the scientific input to policy decisions.

In short, the reliability of a prediction depends on the adequacy of the scientific understanding of the phenomenon addressed, and the utility of a prediction lies in the range of this uncertainty.

Science and Policy

In Transition from Regional to Global Scales. Emphasis in the past understandably has been on needs that are perceived as the most immediate and most local. These have included weather forecasting, urban smog, and acid deposition. However, in recent years, the attention of both scientists and policymakers has extended to more global-scale, longer term changes, such as persistent continental-scale droughts, global warming, coastal erosion, and stratospheric ozone depletion. While the impacts of vital concern remain regional, they are recognized to be embedded in the processes of the larger phenomena.

This enlarging scope has brought to the fore the *interactive nature* of the Earth's environmental systems noted above. For the researcher this implies, for example, seeking to understand not just how climate change can influence regional ecosystems, but also how the Earth's ecosystems influence climate. For the policymaker it implies, for example, basing decisions regarding limitations on the production of chlorofluorocarbons on their role not just in stratospheric ozone destruction, but also in the "greenhouse effect" which may require policies on the limitation of the burning of fossil fuels. Given population growth, increasing industrialization, and the quest for better living standards, the interactive nature of the environmental systems and the policy issues should come as no surprise. The Earth is, after all, one planet and, therefore, contains one interactive "Earth system."

Decisions of Today. The effects of such global-scale changes on the planet have regional impacts that cover a broad spectrum of human activities, e.g., agriculture, habitation, energy usage, forestry, and health care. Equally broad are the associated U.S. economic and policy decisions regarding the well-being of the citizenry and the economic health of the country. Choices must be made regarding agricultural policies, modes of energy production, protection or utilization of natural resources, coastal-zone management, and water-use policies. Reliable information and predictions regarding global changes are required at many decision levels within society: individuals (e.g., farmers), industries (e.g., energy and chemical producers), and regulators (e.g., governments).

Many such decisions are immediate, demonstrating that global change and the needed scientific input to prudent policymaking are not abstract concepts to be dealt with at some future time. The interrelated nature of scientific research and informed decision making is demonstrated by the following questions being asked by scientists and by policymakers:

- Scientists ask:
  - Has a "greenhouse" warming already been detected?
  - What is the uncertainty in the prediction of the magnitude and timing of global warming corresponding to trace-gas increases?
  - How well are the regional consequences of climate change understood and to what extent can they be predicted, e.g., was the 1988 midwestern U.S. drought due to the "greenhouse effect"?
  - What are the hemispheric effects of the antarctic ozone "hole"?

- To what degree do the ice-surface/chlorine/ozone processes discovered in Antarctica cause ozone losses in the Arctic (or globally)?
- What are the potential consequences of the loss of biodiversity occurring from elimination and disruption of habitat due to large-scale conversion of land usage?
- What coastal area problems (e.g., erosion, flooding, and potable water contamination) accompany changes in sea and lake levels and in runoff patterns?
- What regional changes in rainfall are possible due to likely changes in atmospheric circulation?
- What are the ecological and health-related consequences of chemical pollution from industrial processes, agricultural practices, and urban development?

• Policymakers ask:

- Should Congressional actions, particularly those with multiple payoffs, be initiated to reduce the growth rate of "greenhouse" gases in the atmosphere?
- Is the nature of methane emissions known sufficiently well to devise meaningful emission-control strategies?
- Do the provisions of the 1987 "Montreal Protocol on Substances that Deplete the Ozone Layer" need to be strengthened quickly ?
- Should the scope of the Clean Air Act recognize the multiple-issue roles of, for example, the nitrogen oxides in urban smog, rural oxidants, the "greenhouse effect", and acid rain?
- Is it prudent to take international economic actions now to make it profitable for tropical countries to slow down the rate of deforestation?
- What land- and water-management decisions could be made now to make water supply systems more robust in the face of possible precipitation pattern changes?

These questions echo in *current* scientific discussions. They weave through *current* drafts of proposed legislation in the Congress and debate in the regulatory agencies. The scientists rightly seek a defensible understanding of their problems. The policymakers rightly request useful advice on their problems. The points here are twofold: (1) the always challenging dialogue between science and policy is occurring in a new arena - *global change,* and (2) it is occurring *now.*

Needed: A Predictive Understanding of the Earth System

The preceding sections establish the following progression of points:

- *Change is the norm for the Earth's natural environmental systems* (e.g., the Little Ice Age and the Sahelian drought).

- *The Earth's environmental systems are linked through a variety of interactive processes* (e.g., the composition of the atmosphere has been determined largely by the biosphere).

- *In recent history, mankind has become a new and important agent of change* (e.g., widespread "acid rain" in the Northern Hemisphere and global increases in atmospheric carbon dioxide).

- *Changes of both natural and human-induced origin can have enormous impact on human welfare* (e.g., the drastic impact of a single summer's drought on an industrial power and the loss of agricultural productivity following a progression of elevated surface ozone episodes).

- *Science and policymakers both currently face questions that relate to global changes that are occurring now* (e.g., the antarctic ozone "hole" and the debate over the adequacy of the Montreal Protocol).

- *Development of a scientific understanding of a phenomenon can provide the basis for sound policy decisions that mitigate impacts, either observed or predicted* (e.g., the banning by the United States of chlorofluorocarbons as spray-can propellants in 1978).

The underlying premise of this document, and of the U.S. Global Change Research Program, is that wise use of the Earth for human habitation and survival is inextricably linked to an improved understanding of the systems that are undergoing change at varying rates in response to natural and human-influenced processes. A vigorous, well-coordinated Federal research emphasis will be critical to improving predictive understanding and will support the formulation of sound policy decisions. The U.S. Global Change Research Program has been established to provide that vigorous, coordinated effort, as well as effective arrangements for international cooperation.

The Scope of The U.S. Global Change Research Program

The overall U.S. strategy to address global change issues requires efforts in three areas: research to understand the Earth's environment; research and development of new technologies to adapt to, or mitigate, environmental changes; and formulation of national and international policy response options required for a changing environment. The goal of the U.S. Global Change Research Program is to provide the scientific basis for informed decision making. It is not the role of the Program to formulate policies regarding global change, nor does its mandate cover the research required to develop new technologies that might be used to mitigate or adapt to a changing environment.

The CES recognizes that, while alternate technologies are not a component of the Program, high priority should be given to this important research. Agencies such as the Environmental Protection Agency (EPA), Department of Energy (DOE), and U.S. Department of Agriculture (USDA) must play a leadership role in the important area of research in adaptation and mitigation technologies. Such research would be complementary to the U.S. Global Change Research Program and to ongoing studies of response strategy formulation.

The Program's Approach to Global Change Research

This section describes the *strategy* by which the U.S. Global Change Research Program was developed over the past year and by which it will be implemented in coming years.

- State a clear goal for the Program.
- Assess the achievability of that goal, given the current and potential levels of scientific knowledge.
- Identify the known key scientific questions that must be answered in order to gain a better predictive understanding of global and regional changes and their impacts.
- Establish the scientific objectives of the Program. Ask whether meeting the objectives will answer the key questions?
- Define the best scientific approach to meeting the objectives.
- Define the best organizational approach to meeting the objectives. Recognize and address the challenge of effective inter-institutional, interagency, international, and interdisciplinary research.

Program Goal

Recognizing that effective and rational response strategies to environmental issues can be built only on sound scientific information, the overarching goal of the U.S. Global Change Research Program is:

> *To gain an adequate predictive understanding of the interactive physical, geological, chemical, biological and social processes that regulate the total Earth system and, hence establish the scientific basis for national and international policy formulation and decisions relating to natural and human-induced changes in the global environment and their regional impacts.*

Achievability of the Goal

The Earth system is a complex interplay of a variety of processes that operate on a broad spectrum of spatial and temporal scales. Hence, achievement of the Program's goal is as ambitious as it is imperative. Belief that the goal can be met is founded and premised on three conceptual, methodological, and institutional advances that have occurred relatively recently:

- *The sciences essential to an understanding of global phenomena have matured dramatically in the last few decades and are now positioned to address many of the questions that must be answered to truly understand and predict global change.*

  For example, atmospheric scientists, biologists, hydrologists, and oceanographers are addressing the interactions between the atmosphere and the terrestrial and marine environments to examine the linkages between these systems. Focused studies of observations and diagnostic theory of the coupled ocean-atmosphere system in the equatorial Pacific are gaining a predictive capability for this major component of the global climate system. Usefully complete pictures are emerging for some of the processes whereby human activities are influencing substantial parts of the global system (e.g., manmade chlorofluorocarbons and stratospheric ozone).

- *Many of the methodologies and research tools needed to address the global scales of change now exist, are proven, and can be fully exploited in the 1990's.*

For example, Earth-observing satellites now clearly have the potential not only to provide the needed global view of change that is occurring (e.g., vegetation alteration), but also to identify many of the processes involved. Supercomputers are available to run the global-scale models that are now being developed and for establishing effective systems for managing global data sets. Sediment core, ice core and tree-ring techniques "read" the text of Earth system history. Advanced analytical instrumentation is providing the means for measuring many of the reactive trace components of the atmosphere, soils, lakes, and oceans that are the protagonists in the drama of global change. Airborne (e.g., stratospheric research aircraft) and global surface-based (e.g., the Amundsen-Scott Station at the South Pole) facilities are available for observing the details of change on expanded spatial scales.

- *The national and international infrastructures and commitments to a global change agenda are being forged.*

For example, Federal agencies, collaborating with the academic community, have begun in the last few years to describe a cohesive approach to understanding global change and its regional impacts. By Presidential directive, a study was initiated in 1984 by the Office of Science and Technology Policy to "review and define the goals and missions of the various agencies in the area of Earth Sciences research." The resulting report, *"Earth Sciences Research in the Civil Space Program,"* October 1985, recommended, among other things, a standing National Academy of Sciences committee on the global change research issues and the establishment of the FCCSET Committee on Earth Sciences. The report of the Earth Systems Sciences Advisory Committee, *Earth System Science: A Closer View* (NASA 1988), focused attention on the study of the Earth as a single, integrated system and greatly increased the public awareness of the problems and challenges. In addition, these issues were the subject of two National Academy of Sciences reports: *Global Change in the Geosphere Biosphere: Initial Priorities for an IGBP* (1986), and *Toward an Understanding of Global Change: Initial Priorities for U.S. Contributions to the International Geosphere-Biosphere Program* (1988).

In recognition of the need for an effort broader than the climate-change focus of the National Climate Program, the Committee on Earth Sciences was formed to focus and coordinate existing and proposed Federal global change science and related activities.

On the international level, the International Council of Scientific Unions (ICSU) has organized the International Geosphere-Biosphere Programme (IGBP) to focus on understanding the biogeochemical elements of the global system. The IGBP complements the ongoing

World Climate Research Program (WCRP), other elements of the World Climate Program (WCP) of the World Meteorological Organization (WMO), and programs of the United Nations Environment Program (UNEP) and other international organizations.

Key Scientific Questions

A better predictive understanding of the Earth system requires improved answers to numerous questions. Not many complete answers are available at present, but the types of questions, even if currently unanswered, give insight to the structure and nature of the research that is required to provide more and better answers. These questions fall into three major classes: (1) What global change has occurred in the past and is occurring now? (2) What physical, geological, chemical, biological, and social processes are involved in global change? (3) How well can global change be predicted?

What Global Changes Have Occurred in the Past and Are Occurring Now?

The past is a prologue to the present and the future. Namely, the Earth contains records of the changes that have occurred naturally in the global system in the past and that presumably will continue to occur in the future. Therefore, a reading of Earth system history is a global change tutorial that provides: (i) a baseline against which Earth system hypotheses and theories may be tested; (ii) examples of what the natural system may have in store for the future; (iii) the backdrop against which human impact on the system can be identified; (iv) the context in which the magnitudes of predicted future human impact can be assessed; and (v) a lengthy data set that can be used to test the ability of current models to first explain, then predict, changes over long time scales. Questions whose answers are sought in the Earth system history book fall into two categories, based on the source of the answers.

Proxy Record. Questions regarding how the state of the global system has changed over very long time spans must rely for answers on proxy data or indirect evidence: tree rings, sediments, fossils, ice cores, etc. Proxy data provide information about the Earth's climate, oceans, biota, atmosphere, rivers, aquifers, lakes, and land surface up to the present. The information that documents the rapid and slow global changes that occurred leading up to and following the extremes of this glacial epoch is a treasure trove of insight into the interactive processes of the lithosphere, biosphere, and hydrosphere. Answers to the following categories of questions are sought in proxy data:

- *Oceanic extent, circulation, and composition.* What does the sedimentary and fossil record reveal about changes in the existence and extent of deep water masses, sea-surface temperatures, and sea-surface currents (and hence wind circulation and rainfall distribution patterns)?

- *Terrestrial geosphere, hydrosphere, and biosphere.* What biological, physical, and chemical responses of the Earth's surface to global changes are found in the terrestrial records (pollen records; tree rings, soil composition and distribution; fossils; landforms; terrestrial and lake sediments)? What tectonic geological processes (including isostatic rebound, earthquakes, regional subsidence, volcanic eruption, and uplift) and surficial geological processes (including weathering, soil development, and sedimentation) have contributed to global change or contain a record of global change?

- *Atmospheric composition.* What prehistoric changes in atmospheric composition are indicated in air trapped in ice cores and seafloor aeolian sediment distribution patterns? What are the temporal relations (i.e., lead or lag) between these atmospheric composition changes and other indicators of global change (e.g., temperature) that might be used to distinguish between cause and effect?

- *Climate.* What do the records contained in tree-rings; ice cores; lake, terrestrial, and marine sediment cores; and geomorphic features reveal about the extent, duration, and nature of past climatic, hydrologic, and oceanographic conditions?

Direct Measurement. Within the past hundred to two hundred years, modern instruments and observing methods have afforded the opportunity for limited time series of directly measured global change indicators: temperature; rainfall patterns; streamflow and lake and groundwater levels; winds; ecosystem variability; soil chemistry and moisture; changes in oceanic tides, sea level, and currents; variation in solar irradiance; and increasing concentrations of trace gases in the atmosphere. While most of these records are relatively short, the accuracy, precision, and richness of detail reveal subtle, but important, changes on time scales of decades to centuries. Questions that direct measurement can address include:

- *Temperature.* What global and regional temperature changes have occurred over the past century? What uncertainties do the urban "heat-island" effect and marine "bucket" sampling procedures introduce into regional and global temperature trends?

- *Land cover.* How have land use and land cover changed over the past one to two centuries (specifically the extent of forests, wetlands, and managed ecosystems)?

- *Precipitation and water flow.* What shifts have taken place in precipitation patterns? What do historical records of the flows of major rivers and the levels of major lakes reveal about the hydrological cycle over the past centuries?

- *Sea level.* What is the global pattern of sea level variation and what recent changes have occurred? Can the effects of isostatic and tectonic motions and of thermal expansion of oceans be separated?

- *Wind patterns.* What is the climatology of wind patterns, particularly surface winds over the ocean, which drive ocean currents and contribute to poleward heat transport, and how are they linked to evaporation/precipitation patterns?

- *Solar irradiance.* What are the variations in solar output over various time scales?

- *Anthropogenic emissions.* What changes have there been in the human release of key chemicals like carbon dioxide, methane, carbon monoxide, oxides of sulfur and nitrogen, and phosphorus compounds into the rapidly circulating parts of the Earth system?

- *Atmospheric composition.* How has the chemical composition of the atmosphere changed in recent times?

What Physical, Geological, Chemical, Biological, and Social Processes Are Involved in Influencing Global Change and Its Environmental Impacts?

The components of the global system are linked by an amazing diversity of physical and biogeochemical processes, or "forcing agents," that introduce change into the system and transmit change through the system. Most of these are natural processes. But humans also are agents in forcing change (e.g., deforestation and production of "greenhouse" gases). Numerous questions focus on the processes that tie the system (including humans) together. The current paucity of answers is the key limitation in the ability to construct a working model of this global system (for which no instruction manual was supplied).

Global Change Forcing Agents. The global system responds in major ways to (i) changes in solar irradiance, which alters the energy received by the Earth; (ii) changes in atmospheric concentrations of radiatively important trace gases, which determine the "greenhouse effect"; (iii) changes in the aerosol content of the atmosphere, which also affect the radiation balance; and (iv) alterations in land use/cover, which influence biological productivity and diversity and interactions between the surface and the atmosphere. Except for solar irradiance, these forcing agents can have both natural and human-influenced components. On longer time scales, volcanic eruptions, tectonic activity, and changes in the Earth's orbital characteristics play an an important role in changing the Earth's environment.

The most pressing questions associated with these agents are:

- *Solar influences.* What are the short- and long-term changes in the portion of incident solar radiation that influences the energy received, circulated, and stored within the Earth system?

- *"Greenhouse" gases.* What is the range of possible or most probable future atmospheric concentrations of the radiatively important trace gases? How do natural and human-influenced processes contribute to these trends?

- *Aerosols.* What are the clear-air and cloud-related climate forcings that arise from changes in the concentrations of aerosols in the atmosphere? What are the potential contributions to climate-altering aerosols from natural sources and human-influenced sources?

- *Land use.* What types of land-use changes can alter biological productivity and diversity and regional and global climate, and what are possible or likely relevant patterns of future land uses?

- *Human Dimensions.* How will changes in population and human activities impact the global environment?

Global System Interactions. The planetary system is composed of a variety of interactive parts: atmosphere (gases, aerosols, and clouds), oceans (physical, chemical, and biological constituents), solid Earth and land surface (rocks, soils, water, and biotic components including humans), and radiation from and back to space. The system, since it is made up of so many parts that fluctuate on different time periods, has natural variations that can be of large magnitudes. Any change in forcing, either natural or human-induced, causes processes involving these interactive parts to respond, and the global system tends to move toward a new "quasi-equilibrium" state. One of the keys to being able to predict what new state is reached for a particular forcing and its impacts on human activities is an adequate understanding of the processes by which the system responds. Given below are the currently identified major questions that surround global system interactions.

- *Water-radiation interactions.* What land-surface (evaporation, transpiration, rivers, drainage basins, geologic and soil properties, industry, and irrigated agriculture) and atmospheric (winds and precipitation) factors and processes control the atmospheric concentration and distribution of water vapor? As "greenhouse" forcing alters the radiative balance, what changes in evaporation and precipitation will occur, particularly on regional scales? Because of the major "greenhouse" role of water vapor, how will regional changes in evaporation and precipitation in turn influence the radiative balance of the atmosphere?

- *Snow/ice-radiation interactions.* What are the mechanisms whereby the spatial and temporal distribution of snow and ice (both land and sea), hence surface reflectivity and conductive barriers, respond to mean global temperatures changes? How will a change in snow/ice cover alter the radiative balance of the atmosphere?

- *Cloud-radiation interactions.* What natural or human-influenced processes control the distribution and nature of clouds, whose radiative properties influence reflected incoming solar radiation and trap outgoing terrestrial radiation? How will these distributions and properties respond to global and regional changes, such as increased evaporation?

- *Atmospheric composition-radiation interactions.* As the trace gas composition of the troposphere changes, how will the chemical, physical, and radiative processes that control the chemical composition of the stratosphere respond (e.g., concentration and distribution of ozone)? How will these changes impact the atmospheric radiation balance and circulation patterns?

- *Large-scale air-surface interactions.* How will atmospheric motions and precipitation patterns respond to a change in surface temperatures, and, in turn, how will these atmospheric motions (e.g., wind stress) affect the properties (e.g., circulation, salinity, and thermal structure) of the ocean's mixed layer and deep water formation?

- *Ocean circulation-heat transport interactions.* How do oceanic circulation processes influence the net flux of heat at the ocean-atmosphere interface (hence influencing the thermal inertia of the planet) and poleward heat transport? How will these processes change with "greenhouse" forcing?

- *Ocean-trace species interactions.* What processes influence the uptake, storage capacity, and release of CO_2 and nutrients. In turn, how will ocean circulation and temperature changes influence these processes? How will changes in temperature influence the release of methane from marine hydrates?

- *Ocean biota-climate interactions.* What are the processes that affect marine biological and ecosystem dynamics? How, in turn, will such changes affect the global budgets of CO_2 and other climatically or biologically important constituents?

- *Biota-hydrology/energy interactions.* What are the processes that control the changes and rates of change in the productivity, areal extent, and diversity of managed and natural terrestrial ecosystems resulting from regional changes in temperature, precipitation, toxification, and soil loss? How do regional and global changes in the biosphere alter the exchange of energy and water between the atmosphere and terrestrial surfaces?

- *Biota-atmospheric composition interactions.* What are the fundamental effects/interactions of trace gases (e.g., carbon dioxide, methane, and ozone) with biota? What are the mechanisms whereby changes in terrestrial ecosystems (e.g., carbon storage and nutrient cycling) affect the fluxes of chemically and radiatively important trace gases to and from the atmosphere? How will these ecosystems, and hence their trace gas fluxes, be affected by changes in climate?

- *Land-coastal ecosystem interactions.* What are the impacts of changes in the flow of nutrients and sediments from major landscapes to coastal ecosystems? How will changes in sea level impact coastal ecosystems and fresh water aquifers?

- *Ocean-seafloor interactions.* What are the magnitudes of the fluxes of heat and volatiles from the sea floor to the oceans, and to what extent do these influence ocean circulation and chemistry?

How Well Can Global Change and Its Impacts Be Predicted?

Changes in global environments over geologic time are clearly indicated in the Earth's record book. These records can be integrated to construct empirical models of past global change. Quantitative assessments of the progression of past, present, and future global states resulting from the actions of climate-forcing agents require the development of a hierarchy of multidimensional models to describe or parameterize the climate response processes noted above. An indication of the validity of such models is their ability to represent the past paleoclimate record and the observations of the contemporary, directly observed global features. With respect to the ability to furnish reliable predictions of future states of the global system due to natural variation or specified human perturbations, the issue is one of confidence level. Some examples of key questions to be asked include:

Model Simulation of the Past. This includes the following two questions:

- *Physical climate.* To what extent can the climatic changes that occurred between the glacial and interglacial episodes be attributed to subtle changes in the Earth's orbit? Are these changes in orbital geometry sufficient to cause glaciation, or do other mechanisms exist?

- *Ecosystems dynamics.* How well can models simulate ecosystem response (ecosystem extent and productivity, rate of migration, type) to past changes in climate?

Model Simulation of the Present. Modeling of the present must consider physical climate and biological responses, as follows:

- *Physical climate.* How well do the models represent the observed temporal variations (e.g., seasonal cycles; biennial oscillations; and longer-term trends in temperature, streamflow and lake levels, and wind patterns) and spatial distributions (e.g., regional rainfall patterns) for a number of key parameters, especially on regional scales? In particular, can the causes of the step-like global temperature increases observed in the 1920's and the 1980's be explained? Has the expected 3/4-degree Celsius "greenhouse" warming signal been seen, i.e., have observations confirmed the predicted changes? If not, why not? Such a temperature increase is consistent with past increases in CO_2 as per our understanding of the "greenhouse effect." It was, however, not predicted in the usual sense. What do the strengths and shortcomings of the simulation imply about the predictive ability of the model?

- *Biological responses.* Can estimates of biological response be scaled so that the limited amount of experimental information about individual organisms, communities, and ecosystems be extended to the analysis of biotic change for regions and the entire globe? What are the spatial and temporal dynamics of ecosystem processes that are useful for large-scale model generalizations? How well can models based on limited flux measurements simulate the relationship between biological productivity and decomposition and the fluxes of trace gases?

Model Prediction of the Future. Use of models to predict the future generate questions about confidence levels and reliability:

- *Global environment.* What is the confidence level in the prediction of an eventual global warming as a result of increasing "greenhouse" gases? Similarly, what is the confidence in the prediction of the timing of such a warming? What are the most confident features of the predicted "signature" of a warming that could serve as the best guide for establishing a new early-warning monitoring system, as well as guidance for "first-step" policy-option considerations?

- *Regional environment.* Is it conceivable that, within the next several years, models will be able to make reliable predictions of regional changes, e.g., of soil moisture? Of sea level rise?

- *Ecosystem responses.* Even when regional environmental changes can be predicted reliably, will the ecosystem (natural and managed) models be developed to a corresponding extent such that reliable "end-to-end" forcing/response calculations can be made? How far is the scientific community from that achievement? What could accelerate the development of the ability to make such Earth system/regional change predictions?

- *Anthropogenic emissions forecasting.* How well do models that incorporate population growth and demography, technological developments, and economic growth predict human induced emissions of trace gases? Specifically, how can limited measurements of anthropogenic sources be used to estimate global emissions of important trace gases?

Implementation Strategy: Scientific Objectives

From the three major scientific questions posed in the previous section, the U.S. Global Change Research Program has formulated three scientific objectives:

Establish an Integrated, Comprehensive Long-Term Program of Documenting the Earth System on a Global Scale

Observational Programs. There is no substitute for actual observations of global change. Accurate time series records have at least three major functions in a global change research program. (i) They warn of changes (natural or human-induced) that have direct environmental impact on human activities, such as sea- or lake-level changes. (ii) The perspective afforded by time series records reveals changes that signal the existence of previously unexpected phenomena, such as the discovery of the antarctic ozone "hole," whose examination revealed new ozone-related atmospheric processes. (iii) Temporal changes in many spatially distributed global change indicators, such as biological diversity, ecosystem extent, temperature, rainfall, land and sea-ice cover, streamflow, and wind patterns, provide observational tests of the ability of models to explain the global system, which is an important measure of their ability to reliably predict future responses to perturbations.

While there are several existing time series of important global change indicators, most record lengths are relatively short (e.g., solar irradiance) or the data quality is somewhat equivocal (e.g., urban temperatures). Furthermore, the long-term stability of the onboard calibration of satellite sensors, which are crucial to global observations, has proven to be a more difficult problem than originally thought.

Nevertheless, it is important to note that the technical capability currently exists to monitor far more of the important global change indicators than is currently being done. Sensitive *in situ* detectors are available, many of which can be operated in a reliable fashion at remote global land or oceanic sites. Satellite and ground-based remote-sensing networks jointly are capable of monitoring changes in vertical structure of the atmosphere. There are, however, many important parameters which we can't yet measure from space, e.g., cloud base height and surface soil moisture. Long-term ecosystem research stations have demonstrated the feasibility of obtaining a large number of sustained time series of ecological data. In general, the key ingredients for high-quality, sustained monitoring are (i) credible assessments of the measurement accuracies, (ii) the early involvement of theory in designing a monitoring strategy and a continued involvement in the interpretation of the data, and (iii) enduring professional and institutional commitments to these endeavors. An extensive, high quality observational program to provide the long-term records of the global change indicators for use in documenting changes in the Earth system, for use in process studies, and for use in the development and testing of conceptual models should be the central element of the U.S. Global Change Research Program.

Data Management Systems. Success with the U.S. Global Change Research Program will depend upon both the acquisition of high quality data that defines the global system over space and time and the data management services that will make the observational information accessible to the global change scientific research community in the most useful manner possible. At the center of a long-term research program for the study of global change must be the development of a comprehensive managed information system. This system must include the means and mechanisms to gather, transmit, validate, process, analyze, archive, model, and disseminate the disciplinary and interdisciplinary data needed to understand and simulate the scientific interactions of Earth processes on a global scale.

Conduct a Program of Focused Studies to Improve Our Understanding of the Physical, Geological, Chemical, Biological, and Social Processes That Influence Earth System Processes and Trends on Global and Regional Scales

The global system has numerous couplings — natural, human-influenced, and human-influencing — among its subsystems. Many of the linkages respond to change, either amplifying or attenuating the effects of forcing agents or natural fluctuations via positive or negative feedbacks. Such feedbacks can be nonlinear, responding minimally to forcings of the system until a critical magnitude is reached and then operating in a dramatically different mode. Furthermore, numerous processes link the land, biosphere, atmosphere, oceans and cryosphere, e.g., wind stress and surface-to-air evaporation, deep-ocean circulation and the oceanic uptake of atmospheric CO_2, and terrestrial and oceanic biospheric emissions and the atmospheric abundance of trace gases. These processes are the building blocks that must be understood to construct a model of the global system that has the ability to explain the current behavior of the system and hence furnish credible predictions of its future natural and/or perturbed states.

The last few decades have seen some progress in defining such couplings. The radiative physics of the trace gases is considered well understood. General circulation models reproduce many observed seasonal global features, although not in a predictively useful way. Substantial predictive capabilities are being demonstrated for subcomponents of the global system (e.g., stratospheric chemistry), and others appear within striking distance (e.g., the El Niño - Southern Oscillation phenomena and their global connections). Unfortunately, in general, models are far more successful on global scales than they are on regional scales.

It is clear that a key challenge of the Global Change Research Program will be to perfect disciplinary and interdisciplinary tools and carry out the process-oriented studies that reveal how the coupled system works.

Develop Integrated Conceptual and Predictive Earth System Models

Expanding knowledge of Earth system behavior is permitting the development of improved concepts and computer-based models, with the ultimate objective of developing predictions of global change and the impacts on human welfare on both global and regional scales. Predictive capability is progressing for many global processes, e.g., linkages between tropical oceanic behavior and global atmospheric circulation and the response of ecosystems to environmental changes, such as the response of forest growth and succession to changes in regional climate and the responses of plants to elevated levels of atmospheric CO_2.

While scientific understanding is increasing and gives rise to confidence that the science is tractable (e.g., an element of predictability for El Niño), there remains much to do if truly integrated models of the Earth system are to be developed. The major modeling uncertainties arise from both inadequate availability of computing capability and insufficient scientific understanding of coupled biological, geological, and chemical processes. The most significant human impacts from global change are expected to be regional in scope, but current climate models cannot forecast accurately at regional scales, nor can they reveal the causes of natural variability. Even with enhanced computing capability, the behavior of the land surface, including soil moisture and run-off, plant cover, clouds, and other factors, cannot yet be reliably built into models because of insufficient fundamental knowledge of the characteristics and processes.

Therefore, this research will include the development, evaluation, and improvement of theoretical and numerical models to provide better representations of individual components of the Earth system (e.g., human activities, atmospheric chemistry, atmospheric and oceanic circulation, and gas and energy exchange between the atmosphere and the land and ocean surfaces). Ultimately, the *long-term* thrust is the integration of those individual representations into comprehensive, interactive models of the whole Earth system, with applications to regional to global scales.

Scientific Approach

The U.S. Global Change Research Program recognizes the need to achieve a greater level of integration among scientific disciplines, but, at the same time, to preserve the strength that comes with the individuality of the single discipline and, indeed, the creativity of the individual investigator. The approach to achieving this is described below.

The Levels of Disciplinary Integration

Most scientific research has been conducted by individuals and supporting contingents and has concerned small, yet significant, questions that are resolvable with such a level of effort. However, the principal problems of the environment, particularly those involving a global scale, are so large and so complex that no single activity can deal with them effectively. Therefore, the problems of global change require interdisciplinary research on a scale not attempted heretofore. Indeed, a number of interdisciplinary programs have already been initiated, and several such programs have already demonstrated success in providing important scientific advances in understanding broad aspects of the Earth system. Through these pioneering interdisciplinary studies, the need for an even broader, more integrated view of the global Earth system has been recognized.

The U.S. Global Change Research Program is the national effort to meet the need for such an integrated view. It must, however, maintain and strengthen the foundation of the single-discipline and interdisciplinary sciences, which are the essential building blocks of an integrated understanding of the total Earth system.

The Global Change Research Program will integrate the three levels of scientific discipline activities.

- *The Single-Discipline Level.* This basic level of activity comprises single-investigator and large-scale programs of theoretical and process-oriented studies, long-term observations, and information systems in traditional scientific disciplines such as oceanography, glaciology, atmospheric chemistry, meteorology, hydrology, agronomy, biology, geography, economics, and sociology. It is here that the basic biological, social, physical, geological, and chemical processes are addressed and fundamental discoveries about them are often made. One example is the theoretical understanding that the antarctic ozone "hole" could arise from ice-surface chlorine chemistry, which was subsequently supported by field measurements.

- *The Interdisciplinary Level.* It is at this level that knowledge of global subsystems is developed and tested. Such interdisciplinary research activities combine small groups of traditional disciplines in joint activities of monitoring, process studies, diagnostics, modeling, scientific assessments, and data management. Examples include studies of atmospheric-biospheric exchange processes, coupled oceanic-atmospheric dynamics, and land-surface/atmosphere interactions.

- *The Integrated Level.* It is here that conceptual and predictive models for the whole Earth system are conceived and developed, diagnostically tested against the results from Earth system laboratory and field investigations, and employed to make global change predictions. Achieving this fully integrated level of long-term observations, process studies, and predictions relating to the Earth system is the overarching aim of the U.S. Global Change Research Program.

The appropriate balance of these levels of disciplinary research will be maintained in the following way:

- Create an integration of global change activities at all disciplinary levels to develop the needed unified concepts and predictive models;

- Make use of these integrated models to guide interdisciplinary studies of global subsystems and single-discipline studies of globally important processes;

- Guide the use of the results of such interdisciplinary and single-discipline studies to improve global models; and

- Support long-term observations, process oriented studies, and predictive modeling, including data management and infrastructure development at all three levels.

The iterative improvements implied by the second and third steps are essential for progress. In the past, interdisciplinary programs have been more affected by discoveries and perceived needs at the single-discipline level than vice-versa. Interdisciplinary activities are now beginning to have a greater influence on single-discipline work. For example, scientists modeling climate have found that current characterization of land is inadequate for the modeling needs and have called upon hydrologists and botanists to provide better descriptions of heat and water transfer. This example highlights the importance of continuing support at all three levels and fostering the flow of influence and information among the three disciplinary levels.

The Current Status of Disciplinary Integration

Numerous single-discipline Earth science endeavors currently exist. In addition, several interdisciplinary endeavors are in place and emerging. This Research Plan focuses on the latter set as the best indicators of where the Global Change Research Program currently stands in its long-term goal of functioning simultaneously on the single-discipline, interdisciplinary, and integrated levels.

The interdisciplinary stage is the context for the scientific structure of the present plan. Specifically, there are <u>seven interdisciplinary science elements</u> that embody the current and immediate-term features of the Program. These seven interdisciplinary elements are given below, along with a brief description of the role of each in the Program:

- *Climate and Hydrologic Systems.* The examination of the physical processes that govern physical climate and the hydrologic cycle, including interactions between the atmosphere, hydrosphere (i.e., oceans, surface and ground water, clouds, etc.), cryosphere, land surface, and biosphere.

- *Biogeochemical Dynamics*. The study of the sources, sinks, fluxes, trends, and interactions involving the mobile biogeochemical constituents within the Earth system, including human activities, with a focus on carbon, nitrogen, sulfur, oxygen, phosphorus, and the halogens.

- *Ecological Systems and Dynamics*. The investigation of the responses of ecological systems, both marine and terrestrial, to changes in global and regional environmental conditions and of the influence of biological communities on the atmospheric, terrestrial, oceanic, and climatic systems.

- *Earth System History*. The uncovering and interpretation of the natural records of past environmental change that are contained in terrestrial and marine sediments, soils, glaciers and permafrost, tree rings, rocks, geomorphic features, and other direct or proxy documentation of past global conditions.

- *Human Interactions*. The study of (i) the social factors that influence the global environment, including population growth, industrialization: agricultural practices, and other land usages, and (ii) the human activities that are impacted by regional aspects of global change.

- *Solid Earth Processes*. The study of geological processes (e.g., volcanic eruptions and erosion) that affect the global environment, especially those processes that take place at the interfaces between the Earth's surface and the atmosphere, hydrosphere, cryosphere, and biosphere.

- *Solar Influences*. The investigation of how changes in the near-space and the upper atmospherethat are induced by variability in solar output influence the Earth's environment.

Scientific Assessments

Associated with this improving conceptual picture will be regular, integrated assessments of the current scientific understanding of global change. These assessments will provide the scientific agencies and community with a clearer view of future research priorities. The accompanying predictions (including uncertainties) of global change that are based on that current understanding will provide decision makers with an updated scientific basis for national and international policy considerations. Indeed, such periodic assessments will be the *primary output* of the Program with regard to aiding policy decisions.

Coordination Mechanisms

The complex scientific agenda and the infrastructure needed to address the programs outlined in this Plan require a careful assessment of existing national and international governmental and nongovernmental science coordinating and facilitating mechanisms and, where necessary, the creation of new ones. Plans are already "in-hand" for some of the science components of an internationally supported global change research effort. Some of these have evolved from the activities of existing science planning mechanisms both in the United States and abroad. These initial elements, some of which are already in the early phases of field programs, have been derived from the work of global scientific programs such as the World Climate Research Program (WCRP) and bodies of the International Council of Scientific Unions (ICSU), such as the Scientific Committee on Oceanic

Research (SCOR). Thus, there are elements of an existing structure to build upon and some examples of success stories to serve as role models.

The planning for and implementation of a broad and comprehensive global change research program will require collaboration and program coordination among many institutions and bodies, which can be broadly identified within three communities that are involved with the science of global change:

- *National and international scientific community.* Including both structured (NAS, ICSU) and informal mechanisms (scientist to scientist) for planning science activities.
- *Government agencies.* Including individual agencies of governments (U.S. and foreign) that support and conduct global change scientific research and the coordinating bodies for these agencies within governments (e.g., the Committee on Earth Sciences [CES]).
- *Intergovernmental science bodies.* Including multi-national bodies such as the World Meteorological Organization (WMO); the United Nations Educational, Scientific, and Cultural Organization (UNESCO); and the United Nations Environment Program (UNEP).

National and International Scientific Community

The international scientific community has evolved a variety of informal mechanisms for planning science programs. These need to be recognized in the total planning effort. Some programs of research are conceived via informal mechanisms and then become parts of more formal mechanisms. Furthermore, informal mechanisms are often used to "scope out" the detailed scientific elements of a program via workshops and other such *ad hoc* planning mechanisms. Ultimately, it is the scientific community that executes the research, both at the single-investigator level and as components of larger efforts, and hence their planning efforts are vital at virtually all levels. Examples are the World Ocean Circulation Experiment, the Joint Global Ocean Flux Study, the International Satellite Land Surface Climatology Program, and the International Global Atmospheric Chemistry program, whose roots began within the scientific community.

A perspective for the biogeochemical element of a global change research effort was developed by a special committee of the National Academy of Sciences, which published a seminal document entitled *Global Change in the Geosphere-Biosphere: Initial Priorities for an IGBP* (1986). This influenced, in turn, the establishment of the International Geosphere-Biosphere Program (IGBP) in the fall of 1986 by ICSU. The National Academies of Science (NAS) and ICSU are central elements of the total planning process for an international Global Change Research Program, core foci of which are the IGBP, other ICSU global programs, and the nongovernmental organizations' facilitation of the components of the WCRP. At the national level, the NAS Committee on Global Change and the other relevant boards and committees (e.g., Ocean Science Board) will be the foci for coordination.

The work of the NAS Committee on Global Change has been instrumental in facilitating the U.S. contribution to the ICSU/IGBP and the development of initial priorities for both the science elements of the U.S. Global Change Research Program and the IGBP. The Committee's high priority recommendations for new scientific research programs in global change are documented in its report *Toward an Understanding of Global Change: Initial Priorities for U.S. Contributions to the*

International Geosphere-Biosphere Program (1988). This Committee will be a key interface between the CES and the National Academy of Sciences and all of the U.S. Earth sciences scientific community.

At the international level, ICSU will be the key coordinating organization, primarily through its Special Committee for the IGBP. ICSU has already prepared initial documents to guide the development of the IGBP. These include Report No. 4, *The International Geosphere-Biosphere Programme: A Study of Global Change —A Plan for Action* (1988), and the forthcoming report on the first meeting of its Scientific Advisory Council. While the ICSU/IGBP Special Committee is the major focus for integrating the international aspects of a Global Change Research Program, other bodies within ICSU will be actively participating in the scientific planning.

Government Agencies

The U.S. Government, working closely with and through the academic science community and the private sector, began a few years ago to examine the need for and the approach to a coherent study of global change and the development of a better predictive understanding. Several scientific program threads have been woven together to develop what is now the U.S. Global Change Research Program. The National Climate Program was established in 1978 to provide an interagency forum for climate research. In 1983 the National Aeronautics and Space Administration (NASA) established the Earth Systems Sciences Committee (ESSC) to recommend a program and implementation strategy for global Earth system studies. This committee's recommendations focused primarily on NASA, the National Science Foundation (NSF), and the National Oceanic and Atmospheric Administration (NOAA). About the same time, both NSF and NOAA initiated planning and coordination efforts for global change research programs; in 1986 NSF established its Global Geosciences Research initiative, and NOAA began its Climate and Global Change initiative.

Out of these and similar efforts evolved the Committee on Earth Sciences (CES), a component of the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET) within the White House. FCCSET is chaired by the President's Science Advisor. The CES is the coordinating mechanism for a broadly scoped U.S. Global Change Research Program; the Program's science plan is detailed in this document. Planning within the CES resulted in a major U.S. global change research initiative. The strategy and FY 1990 budget proposals for this initiative are outlined briefly in the document *Our Changing Planet: A U.S. Strategy for Global Change Research*, submitted to the U.S. Congress with the President's FY 1990 Budget in January 1989.

Internationally, similar government agency planning efforts are evolving to support a global change research program. An example is the recent report to the Advisory Council on Science and Technology by the Natural Environmental Research Council in the United Kingdom, entitled *Our Future World-Global Environmental Research* (March, 1989). As in the United States, however, foreign governments need to coordinate agency-level budgets and programs toward integrated global change research both at national levels and in support of international efforts. Some sort of ad hoc intergovernmental mechanism may be needed to help bring this about.

Intergovernmental Science Bodies

Three intergovernmental science bodies are essential to the implementation of an international program of global change research: the World Meteorological Organization (WMO); the United Nations Educational, Scientific, and Cultural Organization (UNESCO) and its subsidiary bodies, such as the Intergovernmental Oceanographic Commission; and the United Nations Environment Program (UNEP). Other intergovernmental bodies, such as the Intergovernmental Maritime Organization (IMO), may be required to facilitate the implementation of an international global change research program such as that proposed under the IGBP.

A key component of the international global change research effort is the World Climate Research Program (WCRP) and its specialized global programs like the World Ocean Circulation Experiment (WOCE), the Tropical Ocean Global Atmosphere (TOGA) program, and the upcoming Global Energy and Water Cycle Experiment (GEWEX). These programs are central components to the U.S. Global Change Research Program and complementary to the IGBP. The Global Environmental Monitoring System (GEMS), the Global Resource Information Data base (GRID), and other UNEP programs are important additions to the global change research effort and must be linked carefully into the total research program. The Man and the Biosphere (MAB) program and other UNESCO programs similarly will be contributing elements for a global research effort. In addition to multilateral arrangements, there are several important bilateral agreements between governments, e.g., the Environmental and Space Agreements between the United States and the Soviet Union, that can facilitate international research activities critical to the Global Change Research Program.

The Overall Organizational Challenge

While the formal programs of the intergovernmental bodies are vital to an international global change research effort, they also will facilitate implementation of the research programs of individual nations. Thus, the mechanisms by which research is planned and coordinated between the international and national arenas also will have to be strengthened. The WCRP has evolved to a point where many of the national and international arrangements have already been established. It provides an example of some of the arrangements that have been created to facilitate a complex research program that is replete with many elements and organizational details. A simplified view is depicted in Figure 1.

An international research program to study global change will require a careful blending of national and international resources and infrastructures. The challenge ahead is to build carefully on established mechanisms and to create only those new ones absolutely essential to the implementation of the total program. A graphical representation of some of the organizational arrangements that exist and might need to be established for international global change research is depicted in Figure 2. Question marks in this figure indicate where new or strengthened organizational arrangements are required. Building on these national and international efforts, the CES will continue to develop and emphasize a management structure that involves explicitly both national and international partnerships between scientific and governmental organizations. These are essential to a scientifically sound U.S. Global Change Research Program and to one that serves the U.S. interests to the fullest.

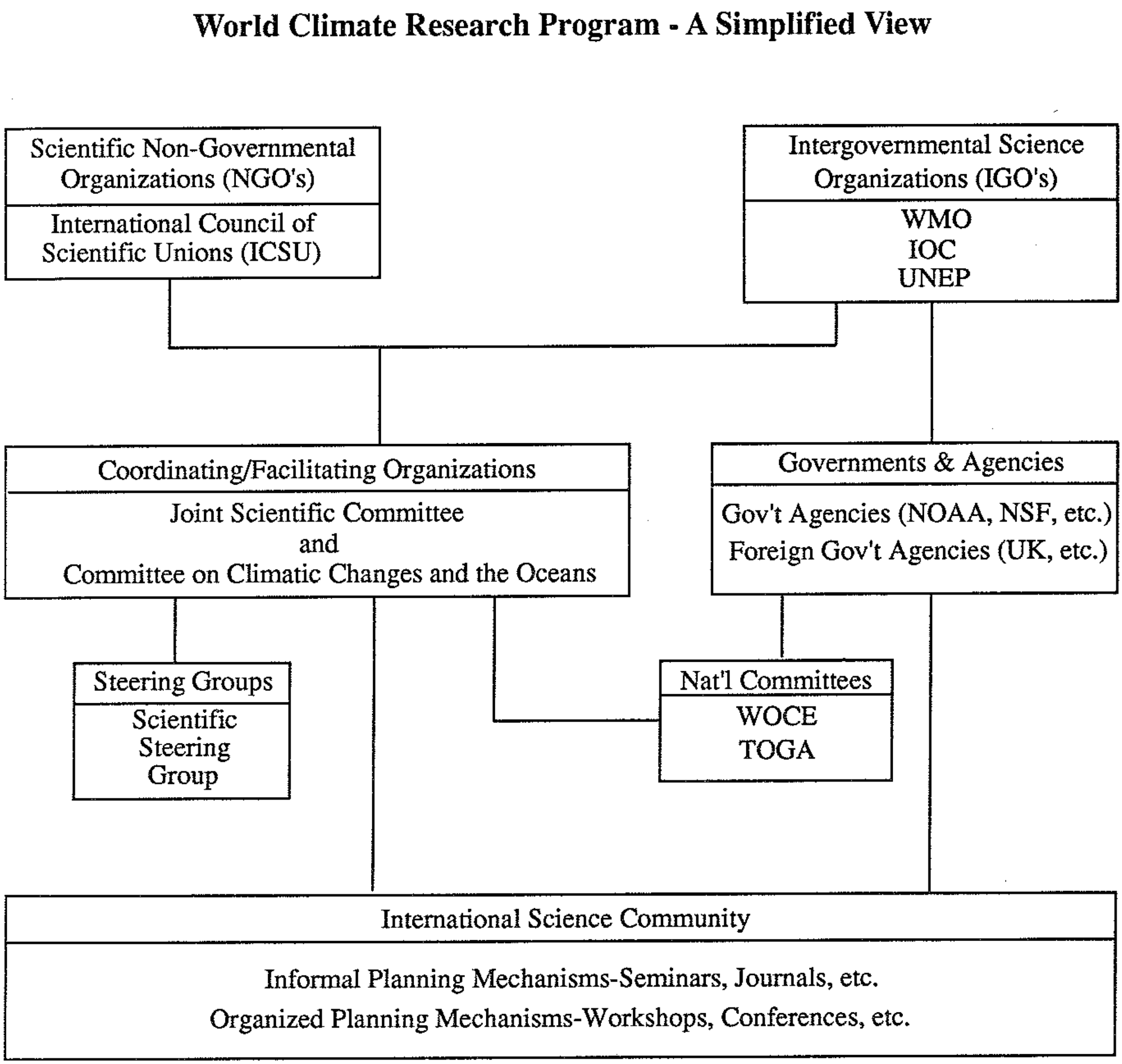


Figure 1. World Climate Research Program: Organizational Structure. The types of components and their interrelations provide an example of an international/national research program.

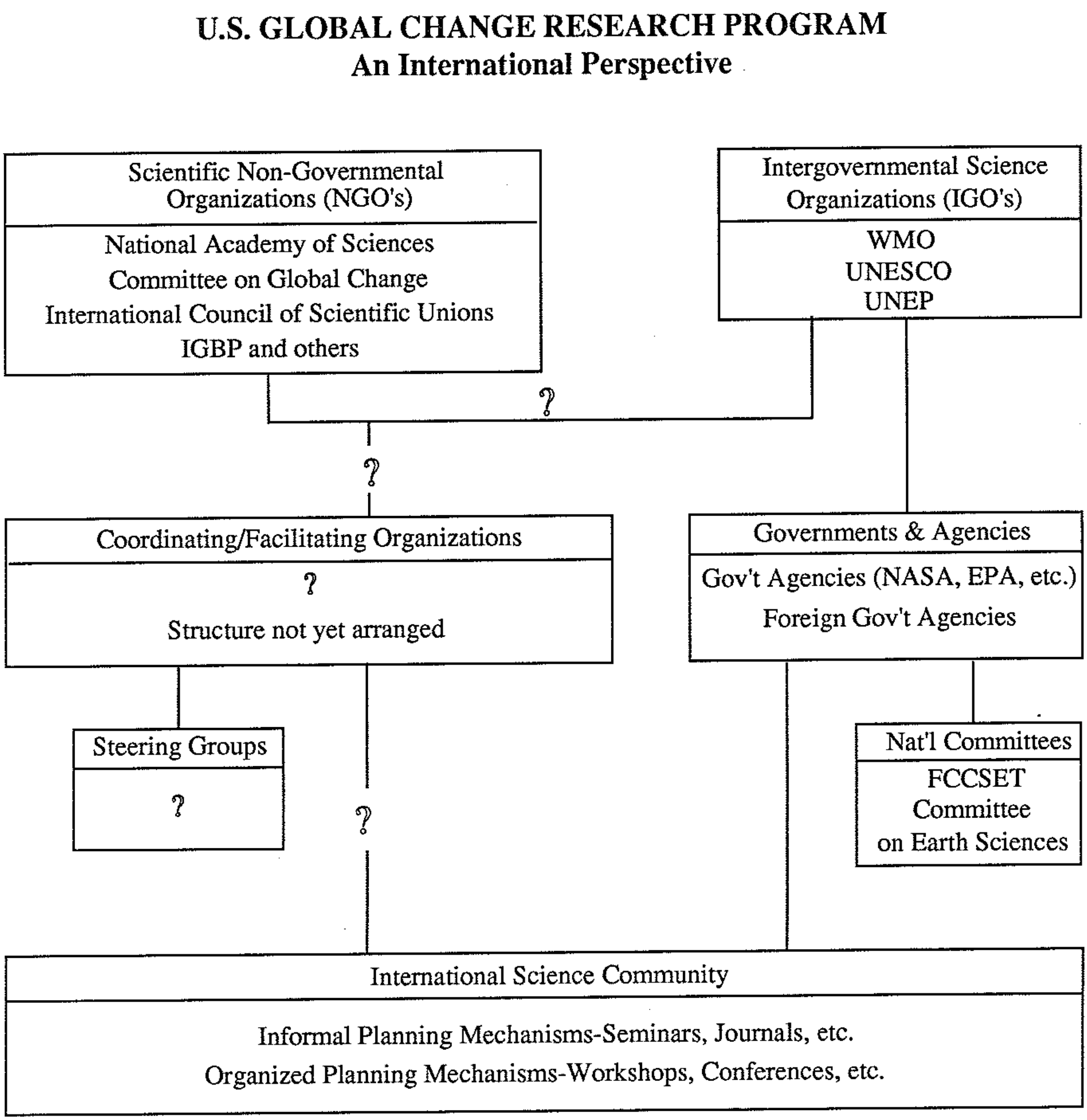


Figure 2. The national and international organizations involved in the planning, coordination, support, and/or conduct of global change research.

The Research Plan: U.S. Global Change Research Progam and FY 1990 Initiatives

The major divisions of this section are the seven interdisciplinary science elements: (1) Climate and Hydrologic Systems, (2) Biogeochemical Dynamics, (3) Ecological Systems and Dynamics, (4) Earth System History, (5) Human Interactions, (6) Solid Earth Processes, and (7) Solar Influences. Many of the current scientific global change endeavors are approximately at this stage of disciplinary integration. An eighth section, "Data Management," is included because success with the science elements will depend largely on the Program's ability to gather, coordinate, integrate, disseminate, and hence utilize the data gained from research and observations.

Within each interdisciplinary science element, the Program is presented according to the three Program objectives: *(1) establishing global-scale, long-term observation systems,* (2) *improving the understanding of Earth system processes, including those associated with human activities, and* (3) *developing predictive Earth system models.* As a measure of the progress in program integration, many of the research activities described below appear under more than one objective, i.e., programs that incorporate observations, process studies, and predictions.

Within each objective, the Program is described in the section (without priority order) in terms of answers to three questions:

- *What are the strengths of the current understanding?* The information on the agency programs given in Appendix B is the basis for the analysis of the current research situation. The summaries in Appendix B are arranged in the following hierarchy: agency; interdisciplinary science element; and the set of long-term observations, research, data management, and facilities. Therefore, for reference, the appropriate parts of the Appendix will be noted simply by giving (*alphabetically*) the agency(ies) involved. In the further analyses (i.e., identifying the high priority research needs), it is assumed that agency support and professional commitments will continue for these current strong and essential elements of the Program.

- *What are the weaknesses in the current understanding and what high priority research is needed to correct them?* Where the current understanding is inadequate to address the key questions, the research needed to fill those gaps is described briefly. Since not all of the needed research can be started here at the outset of the U.S. Global Change Research Program, the high priority components are emphasized.

- *What agency FY 1990 initiatives and/or augmentations address those priority needs?* Since a significant portion of the required research is currently being performed as part of ongoing agency programs (described in Appendix B), this section will highlight the research that is needed to accelerate the development of understanding in key areas. Programs described in this section are FY 1990 initiatives and/or augmentations that are part of the President's FY 1990 budget. In a few exceptional cases, there are entries in this section where new monies have not been requested; they represent significant new efforts through reprogramming of existing funds (these cases are specifically identified). Ongoing agency activities are not described in this section, but can be found in Appendix B.

Climate and Hydrologic Systems

The physical climate and hydrologic systems incorporate the atmospheric, oceanic, and land surface processes that govern atmospheric and oceanic circulations and associated distributions of temperature, moisture, clouds, and precipitation over the surface of the Earth. The system has preferred modes of variability on a number of time scales, and the ultimate effects of man's alterations of the atmosphere and land surfaces will be strongly modulated by the natural characteristics of the system. Some of the components of the system are indicated schematically in Figure 3.

An accurate prediction of the magnitude and timing of a change in climate (changes in the patterns of temperature, precipitation, and severe weather) is limited because of a significant number of uncertainties in the understanding of the physical climate system, including: (i) how clouds modulate the Earth's radiative balance and, conversely, how their distribution may respond to a change in the radiative forcing or aerosol loading of the atmosphere; (ii) how the exchange of energy between the ocean and the atmosphere may change, especially if the circulation patterns of the ocean change; (iii) how the exchange of energy and water will be impacted by changes in albedo (due to changes in land cover and the extent of sea ice, glaciers, and snow cover) and terrestrial vegetation; (iv) how climate and land surface hydrology will interact; and (v) how water is exchanged between ice sheets and the ocean and the effect of this exchange on sea level.

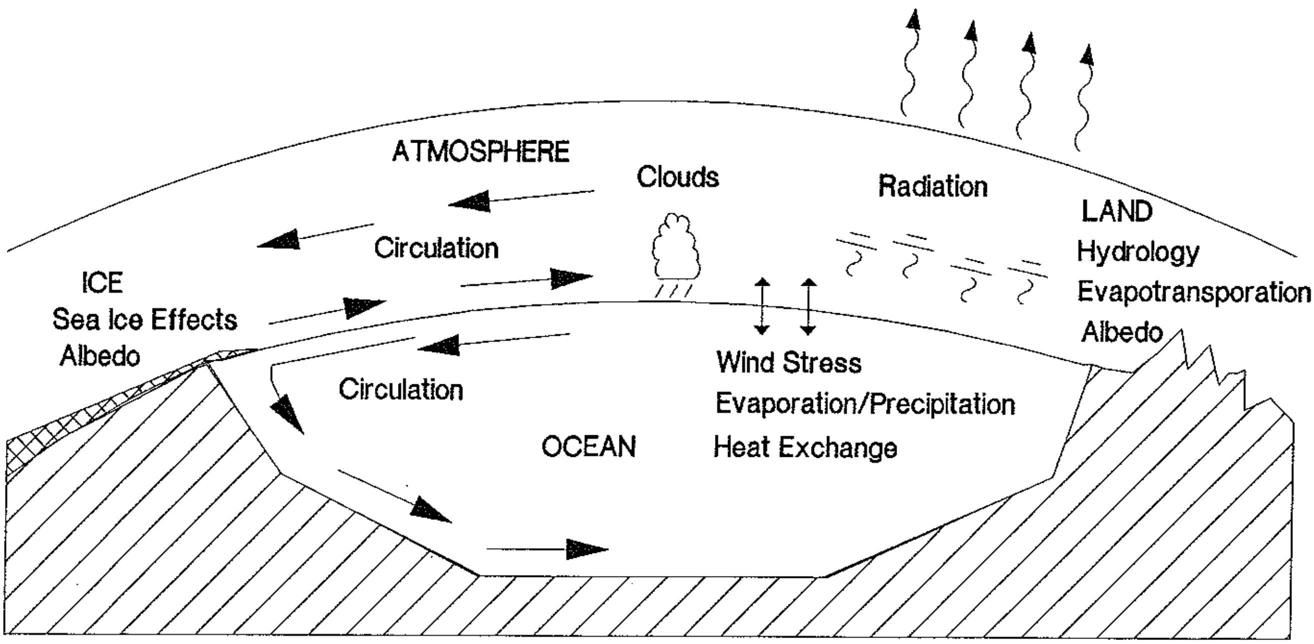


Figure 3. A schematic representation of the components of the physical climate system and some of the significant processes in the fluxes of energy and water.

A predictive capability for the Earth's climate and hydrologic systems will strongly influence our policy responses on a number of major environmental and economic issues:

- *"Greenhouse" Warming*. Natural variability in the climate system, unless accurately predicted, could well obscure extensive mitigation efforts by man. For example, the ocean's huge capacity to store and release both heat and carbon dioxide will strongly influence any global warming signal. A change in net cloud radiative forcing of a few percent would be equal to the radiative effects of a doubling of atmospheric carbon dioxide.

- *Sea Level Rise*. Of major concern to coastal communities are the problems of coastal erosion and loss of wetlands due to changing sea level, a problem closely linked to climate change. Global warming effects could intensify storms, which, coupled with rising sea level, would further increase erosion and storm damage.

- *Water Supplies*. This is one of the dominant public policy issues in arid regions of the country. Prediction of future supplies would allow major decisions on water projects and allocations to be made on a far more rational basis than they are made today.

- *Agricultural Policy*. Crop yields are strongly tied to rainfall, and the 1988 drought had a significant impact on the national economy. The ability to anticipate such an event would have strong implications for farm assistance programs and agricultural trade.

- *Ozone Depletion*. To what extent will changes in stratospheric ozone impact the Earth's climate?

Developing the predictive capability for the physical climate and hydrologic systems that is necessary to provide scientific input to the policy decisions implicit in these issues has three necessary components: global-scale observation, process studies, and simulation and predictive models.

Global-Scale Observations. A combination of *in situ* and satellite-based remote techniques is needed to establish continuous, long-term global monitoring of critical physical variables that characterize the state of the atmosphere, cryosphere, oceans, and land surface. Monitoring techniques are available now for radiation, clouds, vegetation, snow cover, atmospheric and sea surface temperatures, sea level change, glacial and sea ice extent, ocean wind stress, and surface circulation. Techniques for other parameters, including soil moisture and precipitation, involve methods under various stages of research and development that suggest the need for a continuous global monitoring capability. Still others, such as subsurface oceanic circulation, have available techniques (either experimental or operational) that offer less than continuous global monitoring. All of the variables cited are either important indicators of climate change or are important data fields for application with numerical simulation/predictive models.

Process Studies. The variability of the physical climate and hydrologic systems involves the interaction of many dynamic and thermodynamic processes. These processes are of two broad types:

- Those that are essentially internal to one of the main components of the systems, i.e., the atmosphere, oceans, land, and cryosphere. These are mainly responsible for the modes of variability within the components, as well as the characteristic time constants of response.

- Those that govern the interactions and feedbacks between the main components of the climate and hydrologic systems. These are mainly the fluxes of heat, momentum, and water.

Simulation and Predictive Models. The understanding and prediction of the complex responses of the fully coupled climate and hydrologic systems can be achieved only through development of increasingly sophisticated simulation models. These models must ultimately couple the atmosphere, oceans, ice, land, and biosphere, and will involve many sub-models that mathematically represent the individual processes at work within and between the coupled components of the systems. Important characteristics of the real system, involving transient responses and rapid transitions, are probably governed by processes operating on spatial and temporal scales below those of existing models, so that progress on climate system models will likely be paced by computational advances, as well as process research for some time.

There is clearly much to be done before the feasibility and optimum form of predictions of the physical climate and hydrologic system can be realized. A description of the major strengths and weaknesses in these three areas and an indication of how these weaknesses are being addressed by the U.S. Global Change Research Program in FY 1990 follows.

Global-Scale, Long-Term Observations of the Climate and Hydrologic Systems

Strengths of Current Observational Programs

(i) Historical Data Sets. Historical land-based and marine meteorological data sets have sufficient duration and scale to be useful in assessing global climate change. Extensive soil moisture, land, glacial advances/retreats, ground water, streamflow, lake levels, sea ice variability, desertification, and vegetation data sets exist for many habitable areas (but with questionable long-term precision and consistency); these also constitute significant historical global change data sets. (NOAA, NSF, USGS, DOE)

(ii) Operational Meteorological Observing System. More than 30 years of advances in numerical weather prediction have led to a global meteorological observing system, although its requirements are largely determined by the needs of the numerical models that provide the basis of weather prediction rather than by climate applications. (NOAA, NSF, NASA)

(iii) Remote Sensing – Meteorological. Advances in remote sensing technology, both satellite and *in situ*, have revolutionized the meteorological observation system. For example, space-derived atmospheric temperature soundings provide the only data available over large parts of the Southern Hemisphere. Satellite remote measurements also have provided the basis for establishing a global cloud climatology and an Earth radiation budget. The International Satellite Cloud Climatology Project (ISCCP) is acquiring a global data set of cloud distributions and radiative properties from the operational meteorological satellites dating back to 1983. A regional validation is being pursued through the First ISCCP Regional Experiment. The Earth Radiation Budget Experiment (ERBE) is currently measuring radiation fields both globally and regionally, and a Global Baseline Surface Radiation Station Network is being established to acquire surface radiation fluxes to validate satellite-derived quantities. (NASA, NSF, NOAA)

(iv) Remote Sensing – Oceanic. Remote sensing also has strengthened ocean observational capabilities. Sea surface temperature is now being measured by operational satellites, although there is need

for greatly improved *in situ* calibration in many regions. The application of satellite radar altimetry for sea surface topography has made rapid advances over the last 15 years. Maps of regional sea surface topography are now being produced from the NOAA/Navy GEOSAT program; substantial improvements are expected as a result of the Ocean Topography Experiment (TOPEX/Poseidon), a NASA satellite radar altimeter project designed for global ocean circulation research. NASA is also continuing construction on the NASA scatterometer (NSCAT), which will provide vital surface wind data over the world ocean. (NASA, NOAA, Navy)

(v) Remote Sensing – Sea Ice. Variations in arctic and antarctic sea ice can be monitored from operational spacecraft. Microwave radiometric observations from the Nimbus series of spacecraft, followed by the Defense Meteorological Satellite Project (DMSP), currently provide a 16-year record of changes, and this record will continue into the future. (NASA, USGS, NOAA, Navy)

(vi) Monitoring the Cryosphere. The Landsat series of satellites is in place and can be used to monitor areal fluctuations in glaciers, ice caps, and ice sheets on sequential images. A World Glacier Monitoring Service (WGMS) in Zurich, Switzerland, has been established by the United Nations Environment Program (UNEP) to monitor fluctuations of selected glaciers. In a few countries (for example, Switzerland and Norway), excellent historical glacier fluctuation data sets exist. Satellite-based remote measurement of ice sheet configuration is increasingly possible, as has been established from satellite radar altimetry (Seasat and Geosat). (USGS, NOAA)

(vii) Remote Sensing – Land Surface. Satellite-based remote measurements of other such land surface properties as vegetation index, snow cover, and soil moisture are becoming increasingly reliable. (NASA, NSF, USGS, NOAA)

(viii) Ocean Observations. The capability exists to make intensive observations of the fundamental ocean parameters (sea level, thermal and salinity structure, velocity, tracer distribution, etc.) using a variety of *in situ* and remote techniques. *In situ* capabilities now include rapid underwater sampling, telemetry from floats and buoys, acoustic and electromagnetic techniques that integrate over large spatial scales, and geochemical tracers that provide ocean circulation information. (NOAA, NSF, NASA, Navy, DOE)

(ix) Pacific Ocean Monitoring. Ocean observational capabilities are being demonstrated in the tropical Pacific Ocean, where a large-scale monitoring network is in place providing rapid and nearly continuous measurements of thermal structure, sea level, and limited surface winds. (NOAA, NSF, NASA)

(x) Watershed Monitoring. Experimental watersheds in forest, steppe, and agricultural ecosystems have monitored water yield and quality on manipulated and controlled watersheds for more than 5 years. (USDA)

Weaknesses in Current Observational Programs and High Priority Research Needs

(i) Data Sparse Regions. The existing atmospheric observation system is severely limited over the oceans and remote land areas and is deteriorating. New instrumentation development for the *in situ* atmospheric observation system is minimal. Available atmospheric data for driving ocean models are generally inadequate and, in many regions, rely on interpolation schemes that are also inade-

quate. For example, in the tropical Pacific, surface wind is the single most important input data for ocean models, yet these data must be obtained from widely scattered ship reports.

(ii) Climate Trends. The atmospheric observing system was designed for weather prediction, not climate monitoring, which requires end-to-end system performance evaluation to separate long-term trends in climate data from non-climatic changes due to, for example, instrument calibration drift and station changes. At the present time, not a single meteorological variable is consistently evaluated in this way.

(iii) Inadequate Observations. Several parameters critical for climate study cannot be or are not now adequately observed: water vapor, precipitation, evaporation, near-surface hydrology, snow depth, soil moisture, aerosols, and stratospheric temperatures. Fluxes of heat and water vapor between the atmosphere and underlying surfaces (ocean, land surface, and cryosphere) are poorly quantified.

(iv) Validation of Remotely-Sensed Observations. While satellite measurements allow construction of a planetary radiation budget, these measurements are not well validated, and the time variability of the terms of this budget is not well known.

(v) Land Surface – Albedo. Land surface albedo is not properly characterized due to a lack of bidirectional measurements from spaceborne sensors.

(vi) Ocean Observing System. Only the rudiments of an ocean observing system analogous to that of the atmosphere are now in existence. For example, the thermal state of the ocean mixed layer, which is actively involved in the exchange of heat with the atmosphere, is inadequately measured for modeling purposes. Most of the *in situ* ocean observing system is funded by research programs with limited lifetimes.

(vii) Sea Level. Sea level gauges are inadequately distributed, and conventional instrumentation cannot distinguish between actual changes in ocean volume and land motions. Present satellite altimetry is contaminated by atmospheric effects and is not sufficiently accurate for ocean dynamics purposes.

(viii) Air-Sea Fluxes. Existing information on critical air-sea flux parameters, such as wind stress fields and evaporation, do not meet the requirements for ocean modeling.

(ix) Ice Mass Balance. Our most glaring deficiency in knowledge of the cryosphere is whether Antarctica and Greenland are gaining or losing ice because, with 99.3 percent of the combined volume of the world's ice, changes in their volumes have the greatest potential impact on sea level. A Landsat-type global observing system is needed to provide systematic, repetitive coverage of the ice-covered regions of our planet to monitor and document long-term areal changes in glaciers, ice caps, and ice sheets, especially in the antarctic and Greenland ice sheets.

(x) Polar Hydrology. Small changes in polar terrestrial hydrology can lead to large changes in the physical and chemical characteristics of polar ocean surface water; basic data on all aspects of the polar hydrologic cycle are inadequate for climatic interpretation.

(xi) Regional Hydrology. Some components of the hydrologic cycle, e.g., evapotranspiration, groundwater recharge, and precipitation over land, are not easily measured over large areas. Valid

results from general circulation model simulations are, in part, dependent upon the existence of realistic measures of water balance terms. The lack of such regional-scale measurements introduces a severe shortcoming in the testing of GCM output.

(xii) Historical Observations. At present there are very few global data sets that have been compiled and processed for the specific purpose of monitoring and detecting climate change. A substantial effort to collect and process historical observations into global data sets will be required.

FY 1990 Agency Initiatives and/or Augmentations (Observations)

(i) Enhanced Ocean Observation Programs. One major component will be the implementation of an Atlantic Volunteer Observing Ship Network. Using expendable probes dropped from ships of opportunity, this program will produce distributions of upper ocean temperature and (ultimately) salinity in the Atlantic Ocean, following the example of the successful programs in the Pacific. Also included will be observations of geochemical tracers to obtain time-dependent descriptions of ocean circulation. (Addresses weakness vi; NOAA: FY89=$1.2M, FY90=$2.5M.)

(ii) Increased Deployment for the Global Sea Level Network. This network will be capable of measuring absolute sea level to 1 cm accuracy by making use of existing systems where possible, by deploying new advanced technology systems at selected sites, and by establishing a global absolute geodetic reference framework. (Addresses weakness vii; NOAA: FY89=$1.3M, FY90=$3.0M.)

(iii) *The DOE Climate System Research Program.* This program, which obtains and analyzes climate observations to quantitatively link radiative change and climate change, will be enhanced. (Addresses weakness xi; DOE: FY89=$0, FY90=$1.0M.)

(iv) The World Ocean Experiment (WOCE). The NSF role will be augmented to initiate a large-scale global hydrographic tracer experiment in 1990 to provide basic observations for the description of large-scale water mass distributions and their spatial and temporal characteristics. (Addresses weaknesses vi and viii; NSF: FY89=$1.2M, FY90=$1.3M.)

(v) Ice Sheet Observations. New research will be undertaken to monitor changes in key glaciers by means of remote sensing techniques. (Addresses weakness ix; USGS: FY89=$0, FY90=$0.2M.)

(vi) Earth Observing System. NASA's budget will be augmented to provide comprehensive measurements of the physical climate of the Earth through the Earth Observing System (Eos) mission. These measurements will include the radiation budget of the Earth measured from two polar orbiting platforms at different times of day and night, as well as measurements from the Space Station Freedom sampling all local times over the tropics. The atmosphere will be characterized as to its temperature, winds, and moisture structure from the ground to the mesopause. The topography, surface wind velocity, sea-ice cover, and glacier fluctuations will be monitored using imaging and other radar techniques from Eos. The temperature of the surface will be determined from infrared and microwave imagers. Eos will sample rain rates and cloud properties on a global basis and more intensively over the tropics. (Addresses weaknesses i, ii, iii, iv, v, vi, vii, and ix; NASA: FY89=$2.5M, FY90=$3.8M.)

(vii) *Data Services.* NOAA's Climate and Global Change Program will improve data management support for global change program elements, including data bases on trace gases, global hydrologic cycle, and enhanced support for predictive climate change models on time scales of seasons to centuries. Strengthening of observational networks requires support for activities which lead to climate data bases which meet user requirements and can be easily accessed by the global change community. NOAA will also support an interagency working group to establish and coordinate a Global Change Data and Information System by 1995. (Addresses weakness xii and others; see Data Management section; NOAA: FY89=$1.0M, FY90=$2.0M.)

(viii) *Land Surface Data Systems*. Provide for permanent archive, management, access and distribution of land Earth-science data sets for global change research related to the climate and hydrological systems. Includes transfer of remotely sensed data (e.g., Landsat) to stable storage media, archive of selected USGS data sets for global change, and access to land data maintained by other Federal agencies. (Addresses weaknesses ix and x (observations), v and xii (understanding); USGS: FY89=$0, FY90=$0.9M.)

Improving the Understanding of Climate and Hydrologic Systems

Strengths of Current Understanding

(i) Weather Prediction. The behavior of the atmosphere is relatively well known and predictable on shorter, weather time scales of a few days to a week or so. On longer, climatic time scales, the fundamental forcing mechanisms and their primary effects are known, but the detailed reaction of the many non-linear systems involved is not known. (NOAA, NSF, NASA, DOE)

(ii) Forcing by Radiatively Active Species. The direct perturbations to the radiative balance that radiatively active species play are well understood. (NSF, NOAA, NASA, DOE)

(iii) Water Processes – Atmosphere. The general processes through which water plays a fundamental role in radiation, atmospheric chemistry, and the transport and storage of heat are well understood. (NSF, NOAA, NASA)

(iv) *Ocean General Circulation*. The major dynamic processes that determine the circulation of the ocean are based on classical principles that are rather well understood. (NSF, NASA, NOAA, Navy)

(v) *El Niño – Southern Oscillation*. Significant progress has been made in understanding the tropical ocean and its role in interannual climate change through the Tropical Ocean-Global Atmosphere (TOGA) Project. For example, empirical and dynamical models can simulate some aspects of the evolution of El Niño events. (NOAA, NSF, NASA)

(vi) *Regional Ocean Processes*. Understanding of key regional ocean processes can potentially provide a foundation for basin and global model development. For example:

- Western boundary currents, which play a major role in oceanic and atmospheric processes, have been the focus of several recent successful studies. Considerable effort has been devoted to the Gulf Stream, for example, and a multi-year time series of transport through the Florida Straits has been obtained. (NSF, NOAA, Office of Naval Research [ONR])
- Upper ocean physical processes, such as mixed layer development, thermocline ventilation, and subduction are better understood due to a series of focused studies. These provide the link in coupled air-sea models. (NSF)

(vii) *Ocean Surface Forcing.* Recent progress in understanding the role of ocean surface forcing via winds and fluxes has opened new research opportunities to utilize satellite data and to strive for coupled ocean-atmosphere models. For example, an ocean model of the tropical Pacific, driven by observed winds, can roughly reproduce observed features of the thermal structure. (NSF, NOAA, NASA)

(viii) *Ice Mass Balance.* Glaciologists have a good understanding of glacier mass balance and some aspects of the physics of glacier flow. It has also been determined that individual basins within ice sheets vary greatly in net mass balance. (USGS, NSF)

(ix) *Albedo and Global Radiation Balance.* Significant advances have been made in discerning the roles of land surface and ice albedo in the global radiation balance. (NASA, NSF, USGS)

(x) *Evapotranspiration and Climate.* The process of evapotranspiration of plants or vegetation canopies and their interaction with the climate system are under extensive investigation. (NSF, USGS, NASA)

Weaknesses in Current Understanding and High Priority Research Needs

(i) *Scale Interactions – Atmospheric.* The way in which small-scale atmospheric processes, e.g., convection and cloud-aerosol-radiation interactions, affect larger-scale climate processes is inadequately known. Conversely, the influence of large-scale processes on small-scale events is crucial to understanding climate change and requires substantial research.

(ii) *Abrupt Climate Change.* The stability of the states of the climate system and the potential for abrupt change between them, along with other transient responses, are not understood.

(iii) *Teleconnections.* Teleconnection between regional processes in the atmosphere and corresponding processes in the ocean are known to be important and require substantial research to understand causal mechanisms. For example, there is evidence that the 1988 summer North American drought is tied to sea surface temperatures in the tropical Pacific; more diagnostic work needs to be done to clarify other such remote coupling mechanisms.

(iv) *Atmospheric Trace Species.* The interaction among chemical constituents, radiation, and the dynamics and thermodynamics of the atmosphere needs substantial research, i.e., on the quantitative link between trace species and climate change.

(v) *Global Hydrologic Cycle.* The lack of knowledge of the functioning of the global hydrological cycle, i.e., the role of water throughout the climate system, is a key impediment to climate prediction. In addition, the influence of large-scale atmospheric processes on local and regional hydrologic conditions requires considerable research.

(vi) *General Circulation of the Ocean.* The general circulation of the ocean and the processes by which surface and deep water are exchanged are not well known. In particular, the mechanisms and distribution of poleward heat flux by the oceans are critical climate issues requiring an improved description of the global ocean circulation.

(vii) *Ocean Circulation Changes.* Evidence suggests specific mechanisms through which the ocean undergoes major changes in circulation, which are in turn coupled to interdecadal to centennial climate change; these mechanisms are only vaguely understood.

(viii) *El Niño – Southern Oscillation.* Despite broad advances from research on El Niño-Southern Oscillation phenomena, the mechanisms governing the timing of this global scale climate oscillation are not well understood.

(ix) *Ice Sheet Mass Balance.* The most important area of research in the cryosphere is to determine the mass balance status of the ice sheets in Antarctica and Greenland at the present time, and to determine how their respective mass balances are changing in response to climate warming because of the linkage of negative mass balance in glaciers to rising sea level.

(x) *Sea Ice and the Oceans.* The dynamics and thermodynamics of the interaction between sea ice and the ocean and the influence of sea ice on both ocean circulation and climate require further study.

(xi) *Coupling Mechanisms.* The atmosphere/land surface/ocean/ice coupling mechanisms are not sufficiently known on climate-relevant time and space scales.

(xii) *Hydrologic Cycle.* The influence of large-scale atmospheric processes controlling precipitation anomalies on local and regional hydrologic conditions requires considerable research. Development of a capability for forecasting surface hydrologic conditions over monthly to seasonal time scales first requires an elucidation of the processes causing covariability of climatic and hydrologic conditions through the historic record.

FY 1990 Agency Initiatives and/or Augmentations (Understanding)

(i) *Energy and Water Budgets.* Hydrological cycle investigations involve a range of different activities to address weaknesses in this area. The hydrological research of USGS and NOAA will focus on the energy and water budget aspects of land-atmosphere interactions, including problems of representing spatial variability of available moisture and on relations between hydrologic conditions and large-scale climatic conditions. The Global Energy and Water Cycle Experiment (GEWEX) studies the global water cycle with particular emphasis on the energy and water fluxes in the atmosphere/Earth system. The program will examine the thermal balance of the atmosphere and the exchange of moisture and energy with land, oceans, ice, and snow. It will develop methods of predicting changes in water distribution in the atmosphere and underlying surfaces. (Addresses weaknesses v, xi, and xii; USGS: FY89=$0.5M, FY90=$1.9M; NOAA: FY89=$0, FY90=$0.5M.)

(ii) *World Ocean Circulation Experiment.* Ocean circulation studies will address our lack of understanding of both the general circulation and the specific processes of the ocean that influence climate. The World Ocean Circulation Experiment (WOCE) aims to observe and model the ocean with all of the climatologically important elements of its circulation quantitatively observed. Initial field activities will begin in FY 1990. NOAA process research in this context will focus on the coupling mechanisms between interdecadal climate change and thermohaline circulation, particularly in the Atlantic. (Addresses weaknesses vi, and vii; NSF: FY89=$4.0M, FY90=$6.0M; NOAA: FY89=$0, FY90=$1.5M.)

(iii) *Radiation and Climate Change.* The DOE climate system program will substantially augment research to quantitatively link radiative change and climate change. The specific focus will be to determine the timing and characteristics of climate change. (Addresses weakness iv; DOE: FY89=$0, FY90=$ 3.0M.)

(iv) *Arctic Systems Science.* The NSF Arctic Systems Science (ARCSS) program will be augmented to permit more detailed studies of oceanic dynamics and the air/sea/ice exchange of heat and moisture to better understand the role of the polar regions in forcing atmospheric circulation. (Addresses weaknesses vii, x, and xi; NSF: FY89 = $0.5M, FY90 = $1.5M.)

(v) *Glacier Mass Balance.* The USGS carries out annual mass balance studies on four glaciers in Alaska and one in Washington. Annual aerial and ground surveys of glacier fluctuations are made of selected U.S. glaciers. In FY 1990, the USGS plans to increase its regional monitoring of glacier fluctuation and mass-balance studies in the conterminous United States and Alaska. (Addresses weakness ix; USGS: FY89=$0.2M, FY90=$0.3M.)

(vi) *Tropical Oceans – Global Atmosphere.* The NSF role in the Tropical Oceans Global Atmosphere (TOGA) program will be augmented to further investigate the moisture and heat exchange between the tropical Pacific Oceans and the atmosphere and to prepare for TOGA COARE (Coupled Ocean Atmosphere Response Experiment) proposed in this region in 1992. (Addresses weaknesses iii,viii, and xi; NSF: FY89 = $4.8M, FY90 = $5.4M.)

(vii) *Eos.* The combination of sensors on Eos will provide multi-parameter data to study precipitation processes, snow and ice processes, and air-sea interaction. Rain radar and passive microwave sensors combined with cloud imagers will provide simultaneous measurements of cloud top temperature, rain rate, and the vertical distribution of rain intensity. This will improve understanding of precipitation formation within storms. Repetitive images of snow and ice cover throughout the annual cycle of accretion, modification, and melt will lead to an extensive picture of how these processes interact with other environmental variables such as temperature and terrain. The processes by which the oceans and the atmosphere exchange moisture, trace gases, heat, and momentum will be studied using boundary layer measurements, including wind speed at the boundary, temperature, and moisture. (Addresses weaknesses i, iv, v, and ix; NASA: FY89=$1.3M, FY90=$1.9M.)

Developing Predictive Models

Strengths of Current Models

(i) *Atmospheric GCMs.* General circulation models can simulate much of the synoptic scale behavior of the atmosphere and some of the primary features of the observed global climate, e.g., El Niño-Southern Oscillation events. Several different models give similar projections of future global-average temperature increases for the corresponding "greenhouse" gas scenarios, and climate models can simulate some aspects of the paleoclimatic record. (NOAA, NASA, NSF, DOE)

(ii) *Model-Assimilated Observations.* A solid base of experience has developed in assimilating atmospheric data into general circulation models. (NOAA, NASA)

(iii) *Computational Power.* Substantial improvement in models can be achieved by improvements in computational processing ability alone, and this is continuing to increase rapidly. (NOAA, NASA, NSF, DOE)

(iv) *Coupled Ocean-Atmosphere Models.* Coupled ocean-atmosphere models can simulate the evolution of El Niño events in a rudimentary way and form a basis for organizing ocean observational efforts in the tropics. (NOAA, NSF)

(v) *Basin-Scale Ocean Modeling.* In part due to increased computational capability, major progress in ocean modeling has occurred, particularly in basin-scale models. For example, a model of the North Atlantic that can resolve ocean eddies has been developed. (NSF, NOAA, NASA, Navy)

(vi) *Ocean Model Data Assimilation.* Inverse modeling, which constrains ocean processes by data assimilation, has emerged as a critical component of future research. Within certain limitations, this technique allows diagnosis of circulation and mixing regimes using distribution of properties such as temperature and salinity. (NSF)

(vii) *Land-Surface Processes.* Modest advances in representing vegetation and aspects of land-based hydrologic processes in models are being made. (NASA, NSF, USGS, USDA)

(viii) *Meteorology-Hydrology Interactions.* Models relating the interactions of meteorological and hydrologic processes over relatively short time scales (hours to days) and small spatial scales (watershed size) have reached a relatively advanced state of development. (NASA, USGS, NOAA, USDA)

Weaknesses in Current Models and High Priority Research Needs

(i) *Annual Cycle.* A basic test of climate models is their ability to simulate the annual cycle, i.e., the seasonal changes in the oceans and atmosphere; this is inadequately reproduced by today's models. In addition, climate models cannot yet simulate the changes in the atmosphere or in the hydrologic system observed over the last hundred years. These shortcomings limit confidence in their application to long-term predictions.

(ii) *Clouds and Radiation.* The representation of clouds and their overall effect on the Earth radiation balance is one of the principal limitations of climate modeling today. At this point, although we are beginning to understand the net effect of cloud forcing (i.e., the albedo effect dominates over the "greenhouse effect" globally), the question of how global cloud processes will modulate global warming (i.e., their feedback) remains essentially unknown.

(iii) *Models for Climate Change.* Because of continuing changes in model code and inability to incorporate data that are not transmitted in near real-time, present operational numerical weather prediction models are not suitable for the study of climate change. Numerical weather prediction models also do not generally include physical details that are important for longer time scales, e.g., energy balance processes.

(iv) *Interannual Climate Prediction.* Current forecasts of seasonal climate are empirical and lacking in predictive skill, but the tools for routine model-based climate prediction on seasonal time scales exist.

(v) *Ecosystems.* Current general circulation models cannot provide input at ecologically important regional, ecosystem, or watershed scales. Climate and hydrology models that can bridge the difference between general circulation models and ecosystem scales must be developed.

(vi) *GCM Resolution.* Despite the available computational capability, the research community is severely limited by the resolution required for climate general circulation models.

(vii) *Ocean Processes.* Many key ocean processes are not modeled well, yet are critical to model success. Examples include:

- vertical convection, particularly at high latitudes;
- mixing;
- parameterization of eddies and other physical phenomena smaller than grid scale; and
- stability for long-term computation.

(viii) *Model Assimilation of Ocean Observations.* No global ocean model is yet capable of assimilating ocean observations in the same way that numerical weather prediction models use atmospheric observations.

(ix) *Coupled Ocean-Atmosphere Models.* While coarse-scale coupled ocean-atmospheric models have been developed, major progress needs to be made in this area. In global models, for example, this means that features such as the Straits of Gibraltar are simply not included and that exchanges between the oceans and marginal seas are crudely approximated at best.

(x) *Ice-Ocean-Atmosphere Coupling.* Much improved models are needed to link climate change to glacier mass balance changes and changes in sea level, so that the glacial component of sea level change can be predicted. In addition, second generation, three-dimensional ice sheet models, which include thermodynamics, ocean coupling, and feedback effects of solid Earth deformation, are needed to simulate the present state of the polar ice sheets and to predict the response of ice sheets to climate change. A better model of a marine-based ice sheet, such as the West Antarctic ice sheet, is needed to produce a coupled glacier ice-ocean-atmosphere model.

(xi) *Climate Prediction.* Models capable of simulating the coupled atmosphere/ocean/land surface/cryosphere are critical to successful climate prediction and do not now exist.

(xii) *Terrestrial Hydrology.* Despite modest improvements, the adequate parameterization of variables representing the terrestrial phase of the hydrologic cycle remains a major weakness in the capabilities of existing climate models. Principal shortcomings relate to the high degree of spatial variability of land surface characteristics (topography, soils, and vegetation), spatial variability of precipitation, representation of lateral as well as vertical movement of water in the subsurface, and orographic influences on precipitation and temperature.

(xiii) *Regional Impacts.* Regional terrestrial and near-coastal impacts resulting from large-scale climate changes are beyond the state-of-the-art of existing models, as are tools to evaluate regionally effective mitigation methods.

FY 1990 Agency Initiatives and/or Augmentations (Models)

(i) *Climate Forecast Research Centers.* A program in experimental forecast development is proposed to develop a variety of empirical, statistical, and numerical modeling techniques leading to projections of climate changes on interannual to centennial time scales. A limited number of "climate forecast research centers" will be directed toward model development, model validation and performance evaluation, improved simulations of natural variability in the climate system, and development of techniques to address critical problems in coupled models (such as climate drift, realistic conditions at the ocean-atmosphere interface, and model resolution). A program in seasonal climate forecasting is also proposed to advance from routine weather forecasting into longer, climate time scales by developing the capability to routinely predict major seasonal climate anomalies. (Addresses weaknesses i, ii, iii, iv, vii, ix, x, and xi; NOAA: FY89=$0, FY90=$1.0M.)

(ii) *Climate Diagnostics.* NOAA is developing a program in climate diagnostics to document the climate state on a global basis and to analyze the evolution of climate trends and fluctuations. One of the major activities is the implementation of a Climate Data Assimilation System to routinely assimilate all conventional, satellite, and research data into a homogeneous, self-consistent, global atmospheric data set for climate analysis purposes. Also included under this program is model-based analysis of historical climate data sets and diagnostic efforts on model output itself. (Addresses weaknesses i, ii, iii, and iv; NOAA: FY89=$2.0M, FY90=$3.0M.)

(iii) *Hydrology and Modeling.* USGS, through collaboration with the Geophysical Fluid Dynamics Laboratory (NOAA) and the National Center for Atmospheric Research (NSF), is working to improve the parameterization of those land surface/atmospheric interactions associated with surface and subsurface hydrologic conditions in general circulation and mesoscale models. (Addresses weakness xii; USGS: FY89=$0.2M, FY90=$0.3M.)

(iv) *Water Resource Studies.* USGS is developing methods for conducting integrated assessments of the impact of climate change on the hydrology of large river basins. This work includes (a) studies of changes in streamflow (including seasonal patterns, droughts, floods, and average rates of runoff), ground water recharge, and water quality as a result of changes in climate and (b) salinity effects in estuaries and aquifers due to rising sea level. (Addresses weakness xiii; USGS: FY89=$0.5M, FY90=$0.6M.)

(v) *Water Resource Impacts.* EPA is developing a program to evaluate the sensitivity and potential effects of global climate change on water resources. This program will use existing, modified, or new models to evaluate the regional impact of climate change on water volume, water quality, terrestrial ecosystems, aquatic biota and fisheries, and water management structures and strategies. Relationships between global circulation and biotic regions and hydrologic systems will be investigated to link global climate patterns to regional processes. Effort will be directed at development of regional-scale coupled models of climate, hydrology, and ecology. (Addresses weakness xiii; EPA: FY89=$0.7M, FY90=$2.2M.)

(vi) *Model Intercomparisons.* DOE will extend its model diagnosis program to attempt to understand the physical causes of the differences among models (e.g., clouds, ocean models, etc.), understand reasons for disagreements between models and the climate observations (e.g., processes such as convection), and define requirements for improving models (e.g., increased resolution and time dependent calculations). (Addresses weaknesses ii and v to vii; DOE: FY89=$2.0M, FY90=$3.0M.)

(vii) *Eos*. The Eos initiative will provide support for research on modeling the global climate, assimilating satellite and other data into such models and incorporating realistic parameterizations of fine-scale phenomena in these models. (Addresses weaknesses ii and xi; NASA: FY89=$0.5M, FY90=$0.7M.)

(viii) *World Ocean Circulation Experiment.* The NSF WOCE activities will be augmented to further develop models for improved descriptions of water-mass time scales and circulation in the Southern Ocean. (Addresses weaknesses vii and ix; NSF: FY89=$0.7M, FY90=$0.8M.)

Biogeochemical Dynamics

An essential part of reliably predicting change on a global scale is an adequate understanding of the cycling of the key nutrient elements – carbon, nitrogen, oxygen, sulfur, and phosphorus – through their major reservoirs: (i) the oceanic and freshwater aquatic systems, (ii) the solid Earth component, (iii) the biosphere, and (iv) the atmosphere. These major elements are represented schematically in Figure 4, along with the cycling processes that link them.

Several current and pressing environmental issues hinge on aspects of biogeochemical dynamics, for example:

- *"Greenhouse" Warming*. Growing atmospheric concentrations of radiatively important gases because of increased emission rates from surface sources, like carbon dioxide, methane, and nitrous oxide;
- A*cid Deposition*. Increasing acidification of soils and lakes due to deposition from the atmosphere of sulfur- and nitrogen-containing acids formed by chemical transformations of pollutants emitted from surface sources in other regions;
- *Deforestation*. Release of carbon, primarily carbon dioxide, to the global atmosphere from biospheric reservoirs due to land clearing in the tropics;

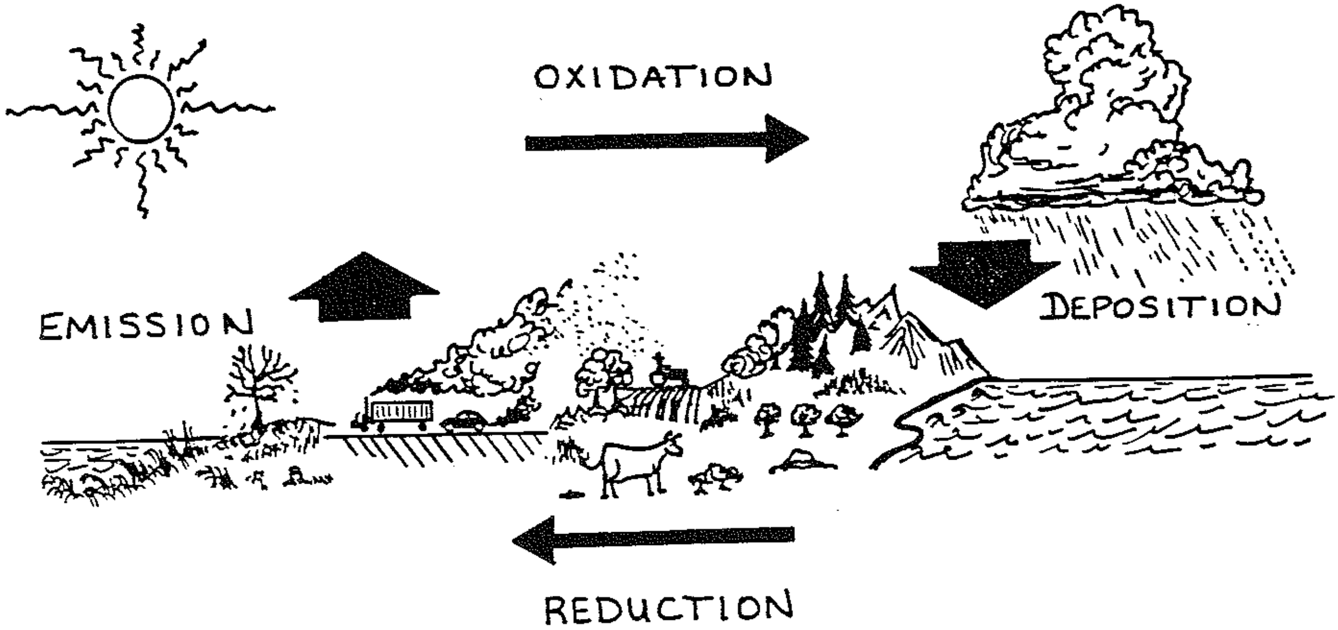


Figure 4. Schematic representation of biogeochemical dynamics: the major reservoirs and the cycling processes that link them. Solar energy drives the system: a gain of oxygen ("oxidation") in the atmosphere and a loss of oxygen ("reduction") in the biosphere.

- *Coastal Pollution.* Perturbations of aquatic systems due to elevated nitrogen and phosphorous; and

- *Ozone Depletion.* Growing atmospheric abundances of trace gases that can decrease stratospheric ozone because of increased emissions rates from surface sources, e.g. chlorofluorocarbons, nitrous oxide, and methane.

Gaining the understanding of biogeochemical cycling necessary to provide scientific input to the policy decisions that are imbedded in these issues has three research components. These are described below.

Long-Term Observations. Establishing the magnitude and spatial and temporal variations of the carbon, nitrogen, oxygen, sulfur, and phosphorous reservoirs defines the total elemental content of the global system and its "ambient" distribution. For example, a crude inventory of the storehouse of carbon, excluding the geological reservoirs, is 2 percent in the atmosphere, 5 percent in the land, and 93 percent in the oceans. Long-term observations of such reservoirs, their component parts, the trends in their magnitudes, and the changes in their distributions furnish vital signals of global change. Such departures from the biogeochemical "quasi-steady state" are a window into changes in the biogeochemistry of the planet, changes that are both perturbations to and responses of the global system.

Furthermore, these trends also are important global change diagnostics that can be used to critically test the ability of global models to simulate the observed temporal behavior of the biogeosphere. The atmosphere, because of its relatively low mass and high mixing, is the reservoir that is the most sensitive indicator of changes. Because of the relative ease with which it can be observed in detail, signs of change are unequivocal, e.g., increasing concentrations of carbon dioxide, chlorofluorocarbons, nitrous oxide, and methane. Indeed, such trends are virtually the only detailed long-term biogeochemical time series. What is happening in other major reservoirs?

Process Studies. As is also indicated in Figure 4, the cycling through the reservoirs, excluding the geological reservoir, involves essentially three groups of transfer processes:

- the biogeochemical processes occurring within the oceans and on the land,

- the geophysical and biological processes that control the fluxes of compounds between the atmosphere and the aquatic (primarily oceanic) and terrestrial biospheres, and

- the meteorological and chemical processes that control the distribution and transformation of chemicals within the atmosphere.

A full elemental cycle is the series of all three. Changes in the processes controlling the fluxes usually cause subsequent trends in the reservoirs, e. g., larger fossil fuel emissions of carbon dioxide cause a subsequent increase in its atmospheric abundance, since the deposition flux out of the atmosphere is largely unaltered. While some individual transformations are known (e.g., the emission factors linking fossil fuel combustion to carbon dioxide release), others are poorly known (e. g., the net flux of carbon dioxide into the ocean). There are significant scientific uncertainties in each of the carbon, nitrogen, oxygen, sulfur, and phosphorus cycles. While biogeochemical cycling can induce global changes (e.g., the buildup of carbon dioxide in the atmosphere), global change can alter biogeochemical cycling (e.g., changes in methane fluxes from alterations in the areal extent of wetlands).

Predictive Models. A predictive understanding of the dynamics of the biogeochemical system requires an integrated picture of the transforming and linking processes occurring over a wide spectrum of spatial scales, e.g., microbiological methane production and regional-to-hemispheric transport of pollutants. A basic modeling requirement is to account for the differences in the spatial distribution of the reservoirs, e.g., couching the inputs so that global proxy data can adequately define the parameters required. Currently, only crude theoretical representations exist on global scales for the major biogeochemical cycles.

Yet the need for a better predictive understanding acutely exists for many aspects of biogeochemical cycles. For example, while it may be possible to define policy options associated with future scenarios for such human-influenced gases like the chlorofluorocarbons and carbon dioxide, it is currently not possible to do so for methane and nitrous oxide because a full picture of the cause(s) for their increases is not yet available. Thus, while long-term observations of the past decade have identified trends that portend a possible "greenhouse" warming problem, an inadequate understanding of the processes that cause the increases prevents predictions of future trends and, of more relevance to policy decisions, prevents defining defensible approaches to altering the trends.

A status report on biogeochemical dynamics research – its strengths, its weaknesses, and what the U.S. Global Change Research Program is doing about the latter in its FY 1990 increment – follows.

Global-Scale, Long-Term Observations of Biogeochemical Dynamics

Strengths of Current Observational Programs

(i) *Ocean Color Sensing*. Satellites (Coastal Zone Color Scanner) have demonstrated the capability to estimate phytoplankton abundance by observing ocean color. These data also provide estimates of the biological productivity of the world's oceans on a global scale and the rate of uptake of carbon by the ocean (NASA). SeaWiFS (NASA), which may fly aboard LANDSAT-6 in 1991 (NOAA), is an improved satellite ocean color sensor designed to provide global estimates of ocean biological productivity. If SeaWiFS does not fly aboard LANDSAT-6 in 1991, there will be an inability to monitor phytoplankton abundance globally for several years.

(ii) *Vegetation Index*. Satellites (Advanced Very High Resolution Radiometer) provide estimates of global vegetation photosynthetic capacity on a daily-to-monthly basis and net primary productivity integrated over the growing season (NASA, NOAA). LANDSAT also provides data useful for detailed vegetation classification, vegetation condition, and surface monitoring (NOAA).

(iii) *Long-Term Ecological Research Sites*. Key ecosystem parameters such as bioproductivity, nutrient cycling (i.e., input-output and turnover of carbon, nitrogen, sulfur, and phosphorus), and hydrological variables of important terrestrial and aquatic biomes (including tundra, tropical forests, grasslands, deserts, and freshwater and marine coastal ecosystems) are observed at NSF Long-Term Ecological Research (LTER) sites, at DOE National Environmental Research Parks, and USDA Forest Service Experimental Forests.

(iv) *Trace Gas (Long-Lived) Monitoring*. Global, ground-based networks exist to accurately monitor the ground-level atmospheric abundances of the long-lived, chemically important and/or radiatively active trace gases, such as carbon dioxide, methane, nitrous oxide, and numerous halocarbons. The emphasis has been largely on remote-area baseline sites (DOE, NASA, NOAA). Global-scale oceanic carbon dioxide measurements are planned as a component of the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS). (DOE, NASA, NOAA, NSF, SCOR)

(v) *Precipitation and Particulate Monitoring*. Regional and limited global-scale networks exist for monitoring (1) the chemical composition of precipitation and the dry deposition of particles, and (2), in polluted areas, the surface concentrations of ozone, carbon monoxide, and other industrially produced gases. (DOE, EPA, NOAA, NSF, USGS, USDA)

(vi) *Monitoring Capabilities*. Observational capabilities (i.e., detection methods and data retrieval techniques) exist for monitoring many key stratospheric chemical constituents using ground-based and satellite techniques, and commitments to future long-term observations of several key constituents (e.g., ozone and nitrogen dioxide) have been made. (NASA, NOAA)

(vii) *Research Satellite*. A major dedicated Upper Atmospheric Research Satellite (UARS) will be launched in 1991 to provide global-scale observations of primarily stratospheric and mesospheric chemical composition, dynamics, and energy input. (NASA)

Weaknesses in Current Observational Programs and High Priority Research Needs

(i) *Trends in Elemental Storage*. Trends need to be determined in the spatial distribution and storage of the major biogeochemical elements within each of the key terrestrial and oceanic ecosystems, with a particular emphasis on understanding carbon cycling (i.e., terrestrial and oceanic biomass, total dissolved carbon in the ocean, carbon dioxide, and methane stored in clathrates).

(ii) *Trends in Environmental Parameters*. Improved understanding is needed of the trends and spatial distribution of the environmental conditions (e.g., temperature, precipitation, and chemical deposition) that influence storage, uptake, and emission of the major biogeochemical elements.

(iii) *Trends in Upper-to-Lower Ocean Fluxes*. Systematic monitoring is needed, over long-time or large-space scales, of (1) the fluxes of trace gases and/or (2) their biochemical precursors and products from the upper ocean to the deep ocean, where materials are then isolated from climate interaction. Emphasis should be on the flux of inorganic and organic carbon. This need will require the development of new *in situ*, unattended measurement systems that can operate for extended periods in remote areas and under harsh conditions.

(iv) *Distribution and Trends of Surface/Atmosphere Fluxes*. Studies are required of the spatial and temporal variability, as well as the long-term trends, of the fluxes of key trace gases and particulate material between the atmosphere and all relevant oceanic and terrestrial ecosystems, as well as anthropogenic sources, both at the regional and global scales. The three major priorities are: (1) uptake and release patterns of carbon dioxide from the major ocean basins and terrestrial ecosystems, (2) escape of chemically reactive pollutants from the continental boundary layer to the global "free" troposphere, and (3) emissions of methane and other natural hydrocarbons. These needs will require the development of simple methods for making systematic long-term measurements of trace gas fluxes and aerosols over large spatial scales at remote sites.

(v) *Trends in Flux-Relevant Ecosystems.* Understanding is needed of trends in the spatial extent and characteristics of key ecosystems that are highly active in the exchange of chemically important and radiatively active trace gases with the atmosphere (e.g., wetlands, peatlands, and permafrost areas that are an important source of methane), and of trends in ecosystem conditions that influence gas exchange rates, e.g., surface temperature, soil moisture, and stress factors.

(vi) *Trace Gas (Intermediate Lifetime) Monitoring.* Measurements are required of temporal trends, spatial distributions, and vertical profiles of the atmospheric concentrations of trace gases with intermediate lifetimes (e.g., carbon monoxide and many of the non-methane hydrocarbons) that (1) affect the atmospheric abundances, hence lifetimes, of the radiatively active trace gases or that lead to the formation of important tropospheric oxidants, (2) are themselves radiatively active (e.g., tropospheric ozone), (3) are precursors of acid deposition (e.g., sulfur dioxide), and (4) may affect the formation of clouds (e.g, dimethyl sulfide). Emphasis should be placed on species controlling the abundance of radiatively active trace gases, tropospheric oxidants, and stratospheric ozone.

(vii) *Distributions and Trends of Short-Lived Trace Gases.* The spatial distribution and trends of most of the short-lived, chemically active species in both the troposphere and the stratosphere (e.g., hydroxyl radical, nitrogen oxides, nitric acid, chlorine monoxide radical, hydrogen chloride, and bromine monoxide radical) need to be determined. Emphasis should be placed on species controlling the abundance of atmospheric ozone and radiatively important gases, such as methane.

(viii) *Monitoring of the Altitude Profiles of Trace Gases.* Trends in the altitude profiles of the long- and intermediate-lived gases above established surface monitoring sites need to be determined. The emphasis should be on the radiatively active gases such as methane, whose global sources and sinks are being studied. In addition, continental monitoring sites must be established for long-lived gases.

Each of the above will require global observations from space and the establishment of a complementary system of *in situ* and remote-sensing measurements at/from surface sites and aircraft. The ground-based network and aircraft campaigns will provide calibration and/or validation of the satellite measurements and complementary observations of parameters not easily measured by satellites.

FY 1990 Agency Initiatives and/or Augmentations (Observations)

(i) *Global Ocean Flux Monitoring.* The NSF and DOE contributions to the Global Ocean Flux Study (GOFS) (NSF, NASA, DOE and NOAA) have been expanded. The GOFS will include long time-series monitoring of the fluxes of carbon and other key elements (nitrogen, oxygen, and phosphorus) from upper to deep ocean at a few representative locations. (Addresses weaknesses i to iv; NSF: FY89=$0.6M, FY90=$0.7M; DOE: FY90 reprogramming=$1.0M)

(ii) *Ground-Based Stratospheric Monitoring Network.* As part of its Climate and Global Change program, NOAA will expand its component of the recently initiated Network for the Detection of Stratospheric Change (NDSC) (NASA and NOAA). The NDSC will provide continuous time series of (1) temperature and (2) the total column content and the vertical profiles of a number of key stratospheric chemical constituents, including ozone and ozone-related chemicals, at several sites around the globe. The development and testing of remote-sensing instrumentation and analysis methods and the design of the network will be accelerated. (Addresses weakness vii; NOAA: FY89=$0.5M, FY90=$1.0M.)

(iii) *Times Series Data of Vertical Distributions of Radiatively Active Trace Gases.* The expanded monitoring of the Radiatively Important Trace Species (RITS) program occurring as a part of the Climate and Global Change program (NOAA) will include acquiring time series of (1) the vertical profiles of tropospheric ozone and longer-lived "greenhouse" species and (2) intermediate-lived chemically active species like carbon monoxide at baseline global monitoring observatories, e.g., Mauna Loa (Hawaii). (Addresses weaknesses vi and vii; NOAA: FY89=$0, FY90=$0.5M.)

(iv) *Atlantic Island Monitoring Sites.* The recently initiated NSF Global Tropospheric Chemistry program includes the establishment of Atlantic island sites to monitor aerosol and precipitation chemistry and deposition in the important region between North America and Europe. (Addresses weaknesses iv, vi, and vii; NSF: FY89=$0.6M, FY90=$0.7M.)

(v) *Forest Ecosystem Monitoring.* The USDA Forest Service Forest Health and Productivity in a Changing Atmospheric Environment Program is designed to determine the effects of atmospheric change on forest ecosystems in order to determine the effects of forest management activities on the atmosphere. (Addresses weakness v; USDA: FY89=$2.1M, FY90=$3.1M.)

(vi) *Earth Observing System (Eos).* The NASA budget will be increased for the development of remote sensing instrumentation for polar orbiting satellites and the space station in low inclination orbit and for an advanced information system for the Earth Observing System (Eos) (NASA, European Space Agency [ESA], and Japanese Space Agency [JSA]). Eos will monitor many parameters that are indicators of the state of the biogeochemical cycles of the key nutrients, such as the spatial and temporal distribution of tropospheric and stratospheric constituents (e.g., carbon dioxide, carbon monoxide, methane, nitrous oxide, the oxides of nitrogen, ozone, dimethyl sulfide); pigment and phytoplankton concentrations in open and coastal oceans; and terrestrial ecosystem extent, dynamics, and state (e.g., soil moisture, surface temperature, intercepted photosynthetically active radiation, leaf area index, vegetation condition, net primary production). (Addresses weaknesses i, ii, v to viii; NASA: FY89=$1.8M, FY90=$2.6M.)

Improving the Understanding of Biogeochemical Processes

Strengths of Current Understanding

(i) *Small-Scale Biological Productivity Processes.* The environmental factors (temperature, water content, chemical composition, etc.) and processes (mass and energy transport, photosynthesis, plant growth, etc.) that control biological productivity and nutrient cycling in terrestrial ecosystems are fairly well understood at the very small spatial scales (plots and stands of vegetation to watershed scale). (DOE, EPA, NSF, USDA)

(ii) *Terrestrial-Ocean Elemental Cycling.* An improved understanding of continental shelf dynamics of biological, physical, and chemical processes that control the fluxes of carbon and other key biogenic materials between the terrestrial-ocean interface and the ocean boundary currents is being developed. (DOE)

(iii) *Boreal Forest-Atmosphere Interactions.* The Second International Satellite Land Surface

Climatology Project (ISLSCP) Field Experiment (SIFE) will study the interaction between the boreal forest biome and the atmosphere, with particular emphasis on the regional energy balance, carbon balance, and trace gas fluxes. (NASA, NSF)

(iv) *Localized Flux Measurements of Less-Reactive Trace Gases.* Techniques have been developed for highly localized, *in situ*, flux measurements from aquatic and terrestrial ecosystems for most less-reactive trace gases (e.g., methane) that will be useful for process oriented studies. These techniques may also be useful for monitoring non-point sources of anthropogenically produced gases. (NASA, NOAA, NSF, DOE, EPA)

(v) *Improved Analytical Techniques.* Recent analytical advances have been made in several process-related areas of study, for example:

(a) the study of chemical and physical processes in sea water, e.g., more accurate measurements of the biota and the concentrations of dissolved carbon dioxide and ionic species. (DOE, NOAA, NSF)

(b) the *in situ* time monitoring of rates of photosynthesis in the upper ocean using fluorometry and optical methodologies. (DOE, NASA, ONR);

(c) the ability to measure fluxes of water vapor and some other gases across certain well-instrumented landscape-size areas (1 to 2 square km) of managed and unmanaged ecosystems. (DOE, NASA);

(d) the *in situ* measurement of key chemically reactive tropospheric constituents (e.g., the nitrogen oxides) in remote areas, where the instruments have been subjected to rigorous intercomparison experiments. (DOE, EPA, NASA, NOAA, NSF);

(e) the *in situ* and remote sensing measurements of radical compounds (e.g., the halogen oxides) via stratospheric aircraft and ground-based stations, as were utilized in the investigations of the recently discovered antarctic ozone "hole". (NASA, NOAA, NSF); and

(f) the development of accelerator mass-spectrometry techniques for the measurement of very small quantities of carbon-14 and beryllium-10 in environmental systems. (DOE, NSF).

(vi) *Regional Chemical /Transport Processes. In situ* measurements of trace gas concentrations and fluxes coupled with meteorological parameters have demonstrated the importance of understanding atmospheric boundary layer processes. These initial investigations have addressed ecosystems as diverse as tropical forests and the Alaskan tundra. (EPA, NASA, NOAA, NSF)

(vii) *Gas-Phase Chemical Reactions.* The gas-phase chemical transformation processes of the key oxygen, hydrogen, nitrogen, and halogen species in the stratosphere are relatively well understood as a result of laboratory and stratospheric measurements. (NASA, NOAA, NSF)

(viii) *Optical Properties of Trace Gases.* The ability exists to determine the optical properties (e.g., infrared line strengths) of the radiatively active trace gases, such as carbon dioxide, methane, nitrous oxide, and numerous halocarbons. (DOE, NASA, NOAA, NSF)

Weaknesses in Current Understanding and High Priority Research Needs

(i) *Elemental Storage and Cycling Processes.* A need exists for an improved understanding of the factors and processes that control the present distributions, storage, and cycling of the major biogeochemical elements within terrestrial, freshwater, and oceanic ecosystems and how these may respond to changes in the environment. In particular, the processes that control ecosystem biogeochemical cycling at large spatial and long temporal scales are poorly understood. A key question is whether the processes that operate at small spatial and short temporal scales are significant at larger and longer scales. Specifically, the research activities required for an improved understanding should include:

(a) Satellite, surface, and sub-surface measurements of oceanic properties and processes that will lead to an improved understanding of biogeochemical cycles in the ocean, e.g., the processes that remove inorganic carbon from surface waters of the world's oceans via vertical transport to the deep ocean and/or biological activity. The focus will be to study, on both global and regional scales, the processes controlling the fluxes of carbon and associated biogenic elements within the ocean and in exchange with the sea floor and continental boundaries.

(b) Observations and manipulations of natural ecosystems; studies of controlled sites of different sizes (especially large sized or special ecosystem sites); and laboratory investigations to enhance understanding of composition and structure of key terrestrial ecosystems, how the major biogeochemical elements cycle through them, and what processes control the pathways and rates of their cycling.

(c) Observations that lead to an improved understanding of the processes that control the transfer of nutrients and other biogeochemical elements from terrestrial ecosystems into rivers, to estuaries and coastal ecosystems, and, ultimately, to the ocean.

(ii) *Gas-Exchange Processes.* Quantitative understanding of the natural and human-influenced gas-exchange processes operating between the air and the surface is inadequate relative to how they affect the long-lived and intermediate-lived chemically and radiatively important trace gases, particularly carbon dioxide, carbon monoxide, methane, non-methane hydrocarbons, nitrous oxide, the nitrogen oxides, and the sulfur gases. The large-scale geophysical and biological processes that control the fluxes of these gases between the atmosphere and aquatic biosphere and terrestrial biosphere are not adequately characterized. Research should consist of:

(a) Surface and airborne field measurements to understand the processes controlling the fluxes of chemically and radiatively important trace gases between terrestrial, freshwater, and oceanic ecosystems and the atmosphere. Isotopic composition data will be needed to interpret these observations. Emphasis should be placed on (1) development of flux measurement methodologies, (2) the processes controlling the exchange of carbon (e.g., carbon dioxide) and sulfur (e.g., dimethysulfide) between the atmosphere and the ocean's major basins, and (3) the fluxes of carbon (e.g., methane) between the atmosphere and all major terrestrial anaerobic ecosystems and hydrocarbon reservoirs.

(b) Satellite observations of terrestrial ecosystem extent and state (e.g., soil moisture, surface temperature, intercepted photosynthetically active radiation, leaf area index, vegetation condition, net primary production) and oceanic extent and state (surface temperature and phytoplankton distributions).

(c) Laboratory and field experimental studies to understand the impact of climate change on biospheric feedbacks, i.e., the impact on trace gas fluxes. Emphasis should be placed on carbon (e.g., methane), nitrogen (e.g., nitrous oxide), and sulfur (e.g., dimethyl sulfide and carbonyl sulfide).

(d) The development of improved trace-gas and particulate emission inventories and projections based on current conditions and anticipated global changes, e.g., changes in global climate and ocean circulation, or more directly, on projected human activities, such as fossil-fuel energy policies and land-use patterns (see the Section on Human Interactions). These scenarios must include anticipated changes in natural processes, such as soil-moisture and temperature effects on biogenic emissions, and the effect of applying mitigation techniques on the emission of trace gases influenced by human activities.

(iii) *Chemical Transformation and Dynamical Exchange Processes.* Improvements are needed in: (1) the characterization of the homogeneous, and especially the heterogeneous (gas-particle), tropospheric and stratospheric transformation processes of the gases that control the atmospheric lifetimes, and hence abundances, of the radiatively and chemically important species, and (2) the rate and mechanisms of exchange of gases across the tropopause (e.g., water vapor and ozone) and out of the planetary boundary layer (e.g., ozone-related gases). Research should consist of laboratory studies of chemical reactions, development of methods for measuring atmospheric abundances of more of the reactive species, surface and airborne field measurement campaigns, and satellite observations to measure and understand the processes controlling the chemical composition and the dynamical and radiative structure of the atmosphere.

FY 1990 Agency Initiatives and/or Augmentations (Understanding)

(i) *Global Ocean Fluxes.* The NSF component of the Global Ocean Flux Study (GOFS) (DOE, NASA, NOAA, and NSF) will be augmented. GOFS will initially focus on the processes controlling the global marine carbon cycle, emphasizing those biological processes that control the flux of carbon into and out of the oceans, transformations in the upper ocean, and exchange between the upper ocean and subthermocline depths and the sea floor. Data from the SeaWiFS satellite sensor will provide global estimates of oceanic productivity with high spatial and temporal resolution. (Addresses weaknesses i[c] and ii[a]; NSF: FY89=$4.7M, FY90=$5.8M.)

(ii) *Tropospheric Ozone and Methane Chemistry.* The Radiatively Important Trace Species (RITS) program, whose augmentation is a part of the Climate and Global Change Program (NOAA), will address the chemical processes (nitrogen oxide and hydrocarbon reactions) that could explain the apparent increasing trend in tropospheric ozone in the Northern Hemisphere and those (hydroxyl radical chemistry) that influence the global methane trends. This would be an important element of the International Global Atmospheric Chemistry Program (IGACP) proposed by ICSU's International Commission on Atmospheric Chemistry and Global Pollution. (Addresses weaknesses ii[a] and iii; NOAA: FY89=$0, FY90=$1.0M.)

(iii) *Biospheric Influences on Atmospheric Composition.* The NSF Global Tropospheric Chemistry Program of the NSF Global Geosciences Activity will be augmented to address issues related to the processing and cycling of radiatively, chemically, and biologically important species through the atmosphere, with a special emphasis on better understanding the biospheric influences on atmospheric composition. This would be an important element of the IGACP. (Addresses weaknesses ii [a]; NSF: FY89=$3.4M, FY90=$6.4M.)

(iv) *Antarctic Ozone and Biogeochemistry.* The NSF contributions to the National Ozone Expedition will be augmented to enhance the studies of stratospheric ozone depletion over Antarctica and the possible influence that such changes may have on biogeochemical processes in the high southern latitudes. (Addresses weaknesses i[d] and iii; NSF: FY89=$3.0M, FY90=$3.3M.)

(v) *Trace-Gas Emission Factors and Inventories.* The EPA Global Climate Change Program will measure the emissions of important trace gases from both natural and anthropogenic sources to improve emission factors and inventories, study atmospheric chemical transformation processes, and assess the potential effects of climate change on nutrient cycles and trace gas emissions at the ecosystem and regional levels and develop data bases and methods for evaluating their contributions to the global biogeochemical cycles. Initial emphasis will be placed on methane and nitrous oxide. (Addresses weaknesses ii[a] and [d]; EPA: FY89=$ 0.6M, FY90=$ 3.1M.)

(vi) *Process-Oriented Eos Instrumentation Development.* The development of instrumentation for the Earth Observing System (Eos) (NASA, ESA, and JSA) will be augmented to improve the understanding of many aspects of global biogeochemical cycling, such as the processes controlling (a) ocean productivity; (b) the cycling of nutrient elements through terrestrial ecosystems; and (c) the chemical composition of the troposphere and stratosphere. (Addresses weaknesses ii[b] and [d], and iii; NASA: FY89=$0.9M, FY90=$1.3M.)

(vii) *Carbon- and Sulfur-Related Biotic Processes.* As part of its Climate and Global Change program, NOAA will extend its biogeochemical research to initiate two ocean-oriented research thrusts aimed at understanding (1) the biotic processes that influence the fluxes of carbon dioxide between the atmosphere and the open ocean, and (2) the role of marine sulfur emissions in forming cloud condensation nuclei, hence influencing albedo. (Addresses weaknesses ii[a] and [c]; NOAA: FY89=$0, FY90=$0.5M.)

Developing Predictive Models

Strengths of Current Models

(i) *Simulation of Small-Scale Ecosystem Process.* Detailed simulation models of key ecosystem processes exist, but they operate at relatively small scales for terrestrial systems (e.g., leaf, site, and stand), although they have not been rigorously tested or validated. (DOA, DOE, EPA, NSF, USDA)

(ii) *Stratospheric (Non-Polar) Chemistry.* Theoretical gas-phase chemical models now simulate, with a fair degree of accuracy, the chemical composition of the unperturbed (non-polar) stratosphere, i.e. the concentrations and partitioning of key oxygen, hydrogen, nitrogen, and chlorine species. (DOE, NASA, NOAA, NSF)

(iii) *Regional Chemical/Transport Processes.* Emerging coupled chemical/transport ("Eulerian") models are beginning to reveal some features of rural chemistry that match new observations, such as high rural ozone episodes, and the phenomenon of acid deposition, where the comparison to results of field campaigns is underway. (DOE, EPA, NOAA)

(iv) *Initial Oceanic Carbon Uptake Predictions.* Ocean box diffusion and lateral transport models, coupled with terrestrial ecosystem models, have been developed to estimate carbon uptake by the oceans and predict atmospheric carbon dioxide concentrations for a variety of fossil fuel combustion scenarios. (DOE, NASA, NSF)

(v) *Preliminary Estimates of Future Anthropogenic Trace Gas Emissions.* There are models that can be used to estimate future anthropogenic emissions of some of the important trace species from U.S. sources, e.g., carbon monoxide, carbon dioxide and oxides of nitrogen. (EPA)

Weaknesses in Current Models and High Priority Research Needs

The long-term goal is to develop integrated models of biogeochemical cycling that couple terrestrial, oceanic and atmospheric processes, e.g., the interactions between the biogeochemical, hydrological, and physical climate system. Specifically, there is a need to develop:

(i) *Upper-Ocean Models.* Three dimensional models of the upper ocean in which the thermodynamics, the fluid dynamics, the chemistry, and the biological processes are fully interactive.

(ii) *Coupled Dynamical Biogeochemical -Atmosphere-Ocean Models.* Ocean general-circulation and basin-scale coupled ocean-atmosphere models that adequately account for the physical, biological, and chemical processes governing the uptake and release of carbon dioxide and other biogeochemical elements and that include shelf-water processes.

(iii) *Climate Change and Ocean Productivity and Circulation Models.* Models that would ultimately permit the prediction of (1) the effects of climate change on ocean productivity and (2) the effect of changes in ocean circulation on the ability of the oceans to sequester and store atmospheric carbon dioxide.

(iv) *Coupled Ecosystem-Atmosphere Models.* Mechanistic models of ecosystem processes that operate at the landscape to regional to global scales and that can be linked to atmospheric chemistry or global climate models.

(v) *Ecosystem Models with Nutrient and Hydrology Interactions.* Mechanistic models of biogeochemical cycling at a hierarchy of spatial and temporal scales in specific terrestrial, freshwater, and oceanic ecosystems that incorporate nutrient interactions and the hydrological cycle.

(vi) *Scaling of Ecosystem Processes.* Theoretical models that connect chemical and physical atmospheric models to terrestrial ecosystems and that establish mathematical understanding of small-scale ecosystem processes in relation to large-scale regional and global systems.

(vii) *Use of Satellite Data as Input to Trace Gas Exchange Models.* Models of trace-gas exchange and ecosystem biogeochemical cycling that can be "driven" by satellite and ground-based observations of the biologically and physically (surface temperature, winds, etc.) driven trace gas fluxes between the terrestrial, freshwater, and ocean ecosystems and the atmosphere.

(viii) *Coupled Dynamical, Chemical, and Radiative Atmospheric Models.* Models of the troposphere and stratosphere in which the dynamics, chemistry (both homogeneous and heterogeneous), and radiation are fully coupled and interactive. In particular, there is need to predict the climatological and chemical factors that influence heterogeneous processes.

(ix) *Chemical Exchange Models.* Models that can accurately simulate (1) the exchange of energy and chemicals between the stratosphere, troposphere. and planetary boundary layer and (2) how changes in stratospheric and tropospheric ozone could influence the Earth's climate system.

(x) *Mechanistic Carbon Dioxide Models.* Mechanistic models: (1) of the physical, chemical, and biological processes that control the exchange of carbon dioxide among terrestrial, oceanic, and atmospheric sources and sinks, and (2) that treat the simultaneous influences of changing atmospheric properties (e.g., the abundance of carbon dioxide) and different climate conditions on fluxes of biogeochemical elements and associated likely positive and negative feedbacks.

(xi) *Human-Interaction/Trace-Gas Models.* Models that can quantify the effects of human activities and climate change on the global and regional emissions of radiatively active trace gases.

FY 1990 Agency Initiatives and/or Augmentations (Models)

(i) *Global Ocean Flux Models.* The NSF component of GOFS (DOE, NASA, NOAA, and NSF) will be augmented. GOFS includes a strong focus on both diagnostic and prognostic models of the ocean processes (vertical transport, biological transformations, and chemical interactions) that affect the fluxes and transformations of carbon and other biogenic elements within the upper ocean and their exchange with the atmosphere, deep ocean, and terrestrial systems. (Addresses weaknesses i, ii, iii, and vii; NSF: FY89=$0.6M, FY90=$0.7M.)

(ii) *Initial Global Carbon Cycle Models.* The development of time-dependent global carbon cycle models incorporating coupled terrestrial and oceanic ecosystems. (Addresses weaknesses iii and x; USGS: FY89=$0, FY90=$0.1M.)

(iii) *Coupled Dynamical/Chemical Climate Models.* The modeling research in the Radiatively Important Trace Species (RITS) program that will be augmented under the Climate and Global Change program (NOAA) will seek to incorporate coupled ozone-related chemical/transport processes in a hierarchy of models, including a general-circulation model, to compare diagnostic and time-series data on the vertical profiles of tropospheric ozone and other trace gases. (Addresses weaknesses viii and ix; NOAA: FY89=$0, FY90=$0.5M.)

(iv) *Surface Exchange Models.* The Global Tropospheric Chemistry Program (NSF) will be augmented to increase activities on the development of atmospheric chemistry models that can be coupled with models describing transport and biological and physical surface exchange processes. (Addresses weaknesses viii and ix; NSF: FY89=$0.6M, FY90=0.7M.)

(v) *Interdisciplinary Models to Use Eos Observations.* Interdisciplinary theoretical investigations associated with the Earth Observing System (Eos) have been initiated to utilize Eos and complementary data to improve the current predictive capabilities for such phenomena as ecosystem distributions and conditions; biogeochemical fluxes at the ocean-atmosphere and land-atmosphere interfaces; fluxes of carbon and nutrients within terrestrial, freshwater, and oceanic systems; and atmospheric composition. (NASA) (Addresses weaknesses i to ix; NASA: FY89=$0.3M, FY90=$0.5M.)

(vi) Emission Inv*entory Modeling.* The development of a model to estimate global emissions of important trace gases from anthropogenic and natural sources. (Addresses weakness xi; EPA: FY89=$0.2M, FY90=$0.4M.)

Ecological Systems and Dynamics

Ecological systems and dynamics are important to global change as both cause and effect. Ecological systems contain the terrestrial, freshwater, and marine biota that provide food and fiber for humans. Ecosystems provide other "environmental services" through their influences on such environmental attributes as air and water quality, the amount and distribution of surface water and groundwater, and wildlife and human habitats. Therefore, disruption to managed and unmanaged ecosystems has direct effects on our economic and social well-being. Physical variables, such as temperature and precipitation, and biotic interactions ultimately control the distribution of species; some species also are extremely sensitive to chemical toxification. Species, in turn, influence the characteristics of ecosystems, and ecosystems influence the physical environment through such phenomena as reflectance, evapotranspiration, and emissions of radiatively important gases. Therefore, ecosystems with altered structural and functional properties can have feedback effects on the physical and chemical environment.

Ecological systems are not static, but are constantly changing, as underscored schematically in Figure 5. Changes can be caused by natural climatic variability, by inherent periodicity of biological processes, or as a consequence of human activities that alter ecological systems or alter the chemical, biological, or physical characteristics in ways leading to other, usually undesirable, changes.

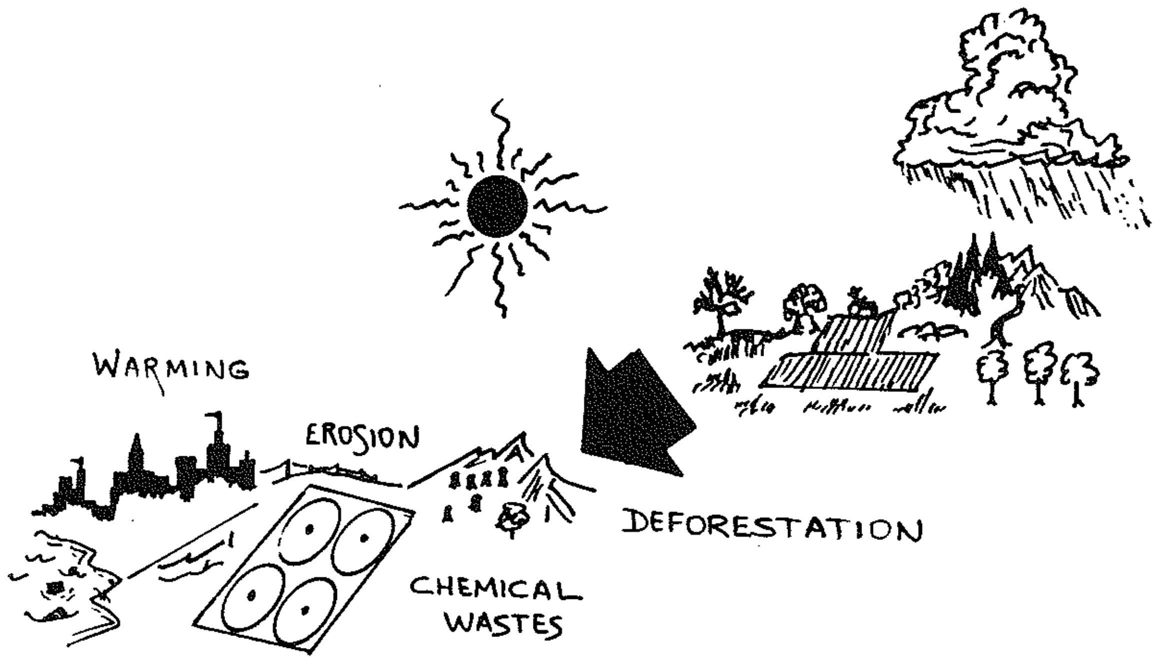


Figure 5. Ecosystem responses to environmental change.

Most current environmental issues bear directly on potential large-scale, unprecedented changes in ecological systems with unknown, but likely undesirable, consequences.

- *"Greenhouse" Warming.* Increased temperature and altered distribution of rainfall may alter species distributions and composition of ecological systems with the potential for feedback effects on the climate system.

- *Acid Deposition.* Increasing acidification of soils and surface waters and addition of sulfur and nitrogen from atmospheric deposition may eliminate "sensitive" and economically important species in some ecosystems and may change ecosystem structure and function (e.g., biological productivity).

- *Biodiversity.* Deforestation in the tropics and other land clearing changes habitats, leading to extinction of species, some of which have never been described; chemical pollution may selectively eliminate sensitive species or genetic strains.

- *Coastal Pollution.* Increased nutrient (nitrogen and phosphorus) input to coastal waters can change species composition and biological productivity and may lead to eutrophication; sediment runoff and chemical waste inputs eliminate species that are ecologically and economically important.

- *Sea Level Rise.* Rise in sea level, which may be caused by warming and land subsidence (natural and man-made), could result in wetland loss and altered biological productivity and species composition and distribution.

- *Erosion.* Erosion of topsoil and associated flooding and sedimentation of lowlands/waterways may alter nutrient dynamics and productivity of managed ecosystems.

- *Ozone Depletion.* Increased UV-B irradiance may affect marine, crop, and other terrestrial ecosystems through its effects on sensitive species (e.g., biogeochemical and physiological processes).

Three research components are necessary to provide scientific input to policy decisions affecting ecological systems: (1) characterization, classification, and monitoring of ecological systems, (2) research on ecological processes, and (3) development of predictive models of ecological system structure and function. Currently our knowledge is far too limited to provide the basis for predictive models.

Characterization, Measurement, and Monitoring. Two main purposes are served by the characterization and classification of ecological systems: (1) to provide a comprehensive picture of the ecological resource base, which is key to relating local/regional phenomena to larger scales of reference, and (2) to highlight systems which may be highly sensitive to change, such as coastal ecosystems, ecotones, etc.

Monitoring of ecological systems is critical to research on global change. Ecological systems are dynamic, responding to internal cycles, normal variations in climatic variables, and recovery following natural disturbances, e.g., fire, flood, wind, etc. Except for the most obvious and drastic of human activities, the principal and often most scientifically controversial question is whether the observed changes in ecological systems stem from natural causes or are of anthropogenic origin. If this question can be resolved it can only come from carefully maintained long-term records (multi-decadal) of ecological dynamics used in combination with an understanding of the processes involved. A related issue concerns the response of ecological systems to past global environmental change (paleo-ecological reconstruction) as a baseline against which to interpret future change; this is discussed in more detail in the section on Earth System History.

Research on Ecological Processes. Biological processes control the interactions of the biosphere with the physical climate system through emissions of radiatively active gases and water vapor. Therefore, interpreting the dynamics of ecological systems in the context of global change requires understanding the underlying processes. Ecological processes mediate many critical steps in global biogeochemical cycles, which are discussed in the previous section. Also, physiological responses to extreme physical conditions, to the dynamics of the physical environment, and related to the ability of plants and animals to reproduce and establish themselves are significant determinants of the geographical limits of individual species.

Developing Predictive Models. A long-term goal of research on global change is to be able to predict the future state and dynamics of ecological systems, in terms of both their feedbacks to the climate system though emissions or absorption of "greenhouse" gases and responses to global change in terms of changing species composition and biological processes. Predictive understanding builds on a knowledge of the distribution of ecosystems and their long-term dynamics and a thorough understanding of ecological processes.

Several steps must occur in order to realize this capability to predict responses of ecological systems (NAS, 1988). Ecological processes are ordered or integrated at different levels of complexity, ranging from individuals to whole ecosystems to coupled ecosystems at various scales. Models and theory need to be further developed and refined at all of these levels and with precision and accuracy of prediction that are commensurate with adequate resolution of the question being asked of the model.

A status report on research on ecological systems and their dynamics follows, outlining strengths, weaknesses, and needs and what the U.S. Global Change Research Program is addressing in FY 1990.

Global-Scale, Long-Term Observations of Ecological Systems and Dynamics

Strengths of Current Observational Programs

(i) *Remote Sensing.* There is a modestly developed capability for large-scale land cover mapping and inventory, including preparation of monthly averaged, global Advanced Very High Resolution Radiometer (AVHRR) vegetation index data for the period 1981 to present and preservation and analysis of fine spatial scale Landsat and SPOT data for selected, climatically sensitive regions of the globe. The existing 9-year record of satellite observations of ecosystem extent and state using AVHRR is being recalibrated and reprocessed to provide greater accuracy about the species observed from the various satellites that have been used to acquire these data. (NASA, NOAA)

(ii) *Fisheries Resources Information.* National Marine Fisheries Service's Pacific Fisheries Environmental Group collects information on climatic influences on the abundance of commercial and marine fish species. (NOAA)

(iii) *Global Ocean Color/Temperature.* Development of a global ocean-color data base from the Coastal Zone Color Scanner provides a map of patterns of ocean primary producer resources. The next generation (SeaWIFS) is being planned for 1991. AVHRR data are used to determine surface temperature patterns. (NASA, NOAA)

(iv) *Ocean Instrumentation. In situ* instrumentation for continuous monitoring of vertical structure and variability of primary producers via fluorometric and optical arrays has been developed and deployed. *In situ* acoustic sampling for planktonic consumer populations is in the early-development stage. Work is continuing on laser and passive optical techniques and multi-frequency acoustic technology to measure biota distributions in real time. (ONR, NASA, DOE, NSF)

(v) *Long-Term Ecological Observations.* A series of 17 sites in representative ecosystems with long-term records of data collection are supported by NSF to undertake programs of long-term observation and experimentation on basic ecological phenomena. At several of the Long-Term Ecological Research (LTER) sites, satellite observational capabilities are being integrated into the programs. Over 30 years of basic environmental data at five DOE National Environmental Parks provide a baseline for determining fluctuations and trends in naturally and artificially stressed ecosystems. The USDA Forest Service operates 83 experimental forests and rangelands and 200 research natural areas throughout the United States, from the tropics to the Arctic, many with over 50 years of data. Ocean ecosystem long time series exist for plankton of the North Atlantic, the California Current Ecosystem, fishery catch statistics, and microbial populations (autotrophs and heterotrophs). (NSF, NOAA, DOE, USDA)

(vi) *Soils Data.* The USDA Soil Conservation Service (SCS) is participating in development of global soils maps. A state-level digital spatial data base is being developed to provide information on influences of climate dynamics on soil processes and soil distribution. SCS also is assisting development of a worldwide map of soils degradation as a consequence of changing climate, mismanagement, and other factors. International archives are at the International Soil Resource Information Centre (ISRIC) in Wageningen, The Netherlands. Assistance will continue with the International Reference Base for Soil Classification, a global land degradation inventory (GLASOD), and a global effort to develop a new world soil map. (USDA)

(vii) *Worldwide Agricultural Yield.* The World Agricultural Outlook Board (WAOB) represents a network of cooperating agencies that provide estimates of agricultural production in real time on the basis of environmental data from a number of sources. (USDA)

(viii) *Advanced Instrumentation.* Instrumentation is being developed to measure plant evapotranspiration of water vapor and other atmospheric gases over large areas (NASA, NSF). Acoustic tomography technology is being adapted to determine *in situ* root system properties of plants. (DOE)

(ix) *Large-Scale Change Detection.* Procedures have been developed that are sensitive to changes in vegetation density as measured by several parameters. These systems are based on coupling remotely sensed data and Geographic Information Systems (GIS) to provide a quantitative analysis of differential changes in spectral values through time (e.g., seasonal, annual). (NASA, DOE, USDA)

(x) *Ecosystem Data.* Ecosystem data are available from a variety of different ecosystems (e.g., shrub-steppe in western North America), providing baseline knowledge of processes controlling energy and material fluxes (including emissions of some "greenhouse" gases). (DOE, NSF)

(xi) *Antarctic Monitoring Sites.* Development of two sites for long-term ecological research in the Antarctic is underway in regions that are believed to be vulnerable to pronounced climatic or environmental change. (NSF)

Weaknesses in Current Observational Programs and High Priority Research Needs

(i) *Ecological Resource Characterization.* Long-term measurements are not sufficient for clearly demonstrating the changes in ecological characteristics at all levels (organisms, ecosystems, biomes, etc.).

(a) Singular variables, such as UV-B irradiance (which may have significant effects on living organisms), are not being monitored on adequate geographic scales of measurement. The network of monitoring and research sites is minimal and much less than is needed to provide a basis for prediction.

(b) Insufficient data are available on long time periods on the structure, dynamics, genetics, and habitat associations of terrestrial animal and plant populations. This situation is equally true for marine ecosystems.

(c) Sampling marine animals to high taxonomic resolution and on appropriate temporal and spatial scales coupled with relevant physical processes is required. In very few systems do we have adequate assessment methodologies for monitoring the distribution and abundance of major animal groups in the sea.

Appropriate sampling and monitoring activities must be developed in order to observe critical changes in the structure of globally relevant biological systems on time scales appropriate for adaptation or mitigation.

(ii) *Coordination of Data Management.* Coordination of ecological (including soils) data management among agencies presently is incomplete. Development of mechanisms and protocols to support a national, and eventually a global, network for ecological data management is needed.

(a) Procedures and computer capability must be developed to a level compatible with needs of the global change program.

(b) Remote sensing data pose special problems. Systematic satellite observations at the finer spatial scales of the Landsat and SPOT sensors are required. While a historical data base has been preserved and archived, there is no systematic program of continuing observations. Furthermore, analysis of existing data has been limited.

Data management and coordination for the entire Global Change Research Program are discussed extensively in a later section of this report.

(iii) *Interpretation of Remotely Sensed Data.* Not enough is known about the biological determinants of reflected, emitted, and backscattered radiation by vegetation to gain maximum ecological interpretation from remotely sensed data.

(a) New, high spectral resolution remote sensing techniques show promise of estimating canopy chemical composition parameters that can be used to elucidate ecosystem properties. Basic understanding and wider validation of this approach are needed.

(b) Alternative methods for large-scale land cover mapping and inventory of ecosystems, which rely on passive microwave sensors, show promise. These methods need to be validated and extended.

FY 1990 Agency Initiatives and/or Augmentations (Observations)

(i) *Earth Observations.* The NASA budget will be augmented for the development of remote sensing instrumentation for polar-orbiting satellites and the space station in low-inclination orbit and an advanced information system for the Earth Observing System (Eos) (NASA, European Space Agency [ESA], and Japanese Space Agency [JSA]). Eos will monitor many parameters that are indicators of the state and extent of terrestrial and ocean ecological systems, including surface temperature, albedo, surface humidity, primary productivity, surface radiation, leaf area, vegetation type and condition, net primary production, soil moisture, pigment and phytoplankton concentration in open and coastal oceans, surface topography (drainage patterns), and landscape patterns. (Addresses weaknesses ii[a] and [b], and iii[a] and [b]; NASA: FY89=$2.6M, FY90=$3.8M.)

Improving the Understanding of Ecological Processes

Strengths of Current Understanding

(i) *Effects of CO_2, Air Pollutants and Climate on Ecological Processes.* Experimental research is providing information about effects of stressors acting singly on plant physiology, ecosystem structure and function, plant/animal interactions, and water balance/hydrology. (DOE, EPA, USDA, NSF)

(ii) *Water Quality Effects Research.* Research on biological response to changes in water quality includes a wide range of ecosystems (wetlands, the Great Lakes, coastal waters, forested watersheds, and, with respect to hazards, deep ocean disposal) and focuses on risk characterization and assessment, often in conjunction with biotic response studies. (EPA, NOAA, USDA)

(iii) *Toxic Substance (including pesticides) Effects.* Process and ecosystem-level research on the transport, transformation, and effects of toxic substances, including pesticides, supports modeling, risk assessment, and integrated environmental assessments. (EPA, USGS, USDA)

(iv) *Basic Research in Ecology.* Ongoing programs support research in ecology, ecosystems dynamics, population biology, biological oceanography, and polar biology that contributes fundamental knowledge on ecological processes and their response to climate and other forcing functions. (NSF, EPA, DOE, DOI, NOAA, USDA, NASA)

(v) *Ecosystem Reconstruction and Species Management.* The Forest Service and Agricultural Research Service (USDA) and National Park Service (NPS) conduct research on developing management options to maintain, correct, and mitigate changes in the structure and function of ecosystems in response to natural and anthropogenically caused change. A similar base of research is ongoing for species populations, e.g., NOAA programs. (USDA, DOI, NOAA)

(vi) *Marine Ecosystems.* Long-term research has developed relationships between light, temperature, nutrients, species, and productivity that can be related to ocean color as measured by satellite sensors. (NSF, NASA, NOAA, ONR, DOE).

(vii) *Research in Conservation and Restoration Ecology.* A special solicitation for proposals dealing with fundamental research that underlies conservation and restoration of biological diversity will be made in FY1990. Appropriate topics will include ecosystems, communities and populations, as well as physiological, genetic and behavioral processes. The competition will also include research on the effects of social and economic factors on restoration and conservation practices. (NSF)

Weaknesses in Current Understanding and High Priority Research Needs

(i) *Fundamental Knowledge of Ecosystem Processes.* Understanding of how species, ecological communities, managed ecosystems, and natural ecosystems (terrestrial, aquatic, and marine) respond to climate is inadequate to interface with and use regional climate information. Both laboratory and field research are required.

(a) Especially critical are large-scale, long-term manipulative experiments involving entire ecosystems. These are necessary for developing and eventually validating ecosystem models.

(b) Another critical research area concerns species interactions, including responses to pathogens and insect outbreaks that often are controlled by climatic variables.

(c) Research is needed to identify elements of biodiversity in terrestrial and marine ecosystems that are most sensitive to change ("indicator" species role), factors affecting the ability of species to adapt, potential methods to maintain biodiversity in the face of change, and the role of biodiversity in ecosystem function.

(d) There is an inadequate basis with which to assess the effects of climate and other external changes on species and ecosystems, particularly when multiple environmental factors change simultaneously (e.g., the combined effects of elevated CO_2, varying temperature, and moisture stress on plant processes or the influence of upland processes on coastal marine ecosystems).

(e) Understanding is needed of interactions between physical and biological processes at different time/space scales and how the large-scale interactions cascade to influence processes down to the microscale (e.g., temperature and ocean circulation effects on biogeography and dispersal; eddy motions on food availability and recruitment; turbulence effects on feeding and reproductive behavior).

(f) There is insufficient understanding of the importance of episodic, storm-scale events and the timing of these events on population variability and ecosystem functioning. Effects may occur on primary production, reproduction, events at critical life-history stages, or successional processes, etc.

(g) The effects of changes of sea level on successional patterns of plants and animals in estuaries and wetlands are unknown. These effects may have consequences on other marine resources well beyond habitats affected directly.

(ii) *UV-B Effects Research.* Laboratory and field experimentation is needed on effects of UV-B irradiance at the Earth's surface to determine for crop, marine, forest, and other ecosystems: (1) biochemical, physiological, anatomical, morphological, and phenological responses; (2) mechanistic bases for response; (3) ranges of sensitivity for cultivars and other species; and (4) mechanisms controlling resistance to effects and possible genetic controls.

(iii) *Soil Processes.* Short and mid-term temporal changes in soil properties related to wind and water erosion, change of cropping or land use, and response to natural and anthropogenic change are poorly understood. Likewise, the influence of soil properties and their distribution spatially is poorly documented and understood. The SCS/USDA has extensive data on tropical and subtropical soil profiles in addition to pedons in the United States.

(iv) *Remote Measurement Technology.* The technology available to measure ecological processes and gaseous emissions from ecological systems remotely is inadequate. Especially required are measurements at appropriate spatial and temporal scales to facilitate modeling of coupled systems (e.g., atmosphere-biosphere).

(v) *Scaling Ecological Parameters.* There is a continuing need to press the development of ways of extrapolating ecological information from local to regional to global scales of reference. Similar questions of scale arise in matching biological process models with models of physical processes.

FY 1990 Agency Initiatives and/or Augmentations (Understanding)

(i) *Basic Plant UV-B Interactions.* Basic research will be conducted to determine the mechanisms of plant response to enhanced UV-B radiation expected from depletion of the ozone layer. (Addresses weakness ii; USDA: FY 89=$4.4, FY90=$7.8M.)

(ii) *Research at the Land-Sea Interface.* To stimulate the basic interdisciplinary research necessary to determine how many types of land-sea interfaces (e.g., estuaries, salt marshes) act as integrated ecosystems rather than simply boundaries. Activities include the quantification of the flux of materials and their transformations through these margin ecosystems and how this contributes to productivity of coastal oceans and nursery grounds of important marine populations. (Addresses weakness i; EPA: FY89=$0, FY90=$0.2M.)

(iii) *Terrestrial Ecosystem Research.* EPA will conduct basic research on the interactions between climate and ecosystems, both managed and unmanaged. Studies will be conducted at several levels of biological organization: (1) individual—physiological effects of CO_2, temperature, and moisture stress; (2) population—reproduction, mortality, competition, etc., as affected by climate; (3) community—relationship of climate and species distribution patterns, biodiversity, etc.; (4) ecosystem—climate effects on productivity, disturbances, succession, etc.; and (6) biotic regions—climatic factors controlling distribution of major biomes of North America. Long-term ecological records and paleoecological data also will be used to understand the impact of global climatic change on ecosystems. This initiative also contributes to an understanding of Earth System history. DOE will develop and augment field instrumentation and conduct research on the combined effects of CO_2 and climate on vegetation. (Addresses weaknesses i[a] to [f]; EPA: FY89=$7.4M, FY90=$12.0M; DOE: FY89=$0, FY90=$2.3M.)

(iv) *Earth Observing System.* The development of instrumentation and the initiation of interdisciplinary observational, analytical, and theoretical studies for the Earth Observing System (Eos) (NASA, ESA, JSA) to improve understanding of the biotic and abiotic factors controlling such ecological processes as productivity, phytoplankton blooms, evapotranspiration, nutrient cycling, population and community dynamics, and vegetation succession. Eos data will provide data crucial for scaling (i.e., interpolating) ecological information from small to large spatial and temporal scales. (Addresses weaknesses i[e], iv, and v; NASA: FY89=$1.2M, FY90=$1.9M.)

Developing Predictive Models

Strengths of Current Models

(i) *Theory in Biological/Physical Systems.* A modest amount of ongoing research is being done to strengthen and expand the theoretical underpinning for complex ecological systems, thereby providing better definition for modeling and experimental design, including experimentation and modeling across varying space and time scales. (DOE, NSF, USDA)

(ii) *Biosphere-GCM Linkages.* Results from simple biosphere models linked to GCMs demonstrate the importance of interactive linking between the atmosphere and the land, because more realistic values of fluxes and more realistic patterns and amounts of rainfall are achieved. (NASA, NSF, DOE)

(iii) *Crop Simulation Models*. Agricultural Research Service (ARS), Soil Conservation Service (SCS), and DOE are supporting development of computer models to simulate plant physiological processes, growth, and yield. Both climatic factors and carbon dioxide concentration are treated as explicit variables. (DOE, USDA)

(iv) *Crop Management Models*. ARS and SCS have developed computerized agricultural decision support models to aid farmers in making choices about allocation of resources such as irrigation, fertilization, and other management factors pertinent to sustaining agricultural production in a changing environment. (USDA)

(v) *Forest Models*. The USDA Forest Service has proposed a long-range forest resource management program that will incorporate: (1) physiologically-based models to predict effects of climate change on forest species; (2) models of yield and linkages to physiological processes; and (3) models of economic impact and risk assessment. (USDA)

(vi) *Ocean Physical Models*. Basin-scale, eddy-resolving community models, as well as larger-scale coupled global ocean/atmosphere models, are now being run on supercomputers. This work is an essential precursor in order to incorporate biological model components in basin and global-scale models. (NASA, NOAA, NSF)

Weaknesses in Current Models and High Priority Research Needs

(i) *Theory and Model Development*. Two areas where model development is especially limited by inadequate theoretical constructs are: (a) ocean biology, and (b) soil formation.

(a) Theoretical constructs and mathematical simulations that couple atmospheric and ocean physics to population dynamics and the structure of ocean ecosystems are needed. The same need exists for atmosphere/terrestrial physical and biological systems.

(b) The concepts of how and when soils form and their stability under varying conditions are generally known only qualitatively. There is a need for soil process research leading to models of soil formation that explain temporal and spatial variability and predict short- and long-term responses to global change.

(ii) *Linked Ecological and Physical Models*. In order to develop predictive ecological models, appropriately linked ecological-physical models must be developed.

(a) Regional air pollution models such as EPA's Regional Oxidant Models (ROM) and Regional Acid Deposition Model (RADM) need to be linked to biotic response models.

(b) Our understanding of the physical environments at small spatial scales relevant to the geographic distribution of terrestrial and marine species and their behavior and life-history ecology is inadequate. Analytical methods and numerical modeling of small-scale physical processes relevant to spatial patchiness of plant and animal population are needed.

(c) Models are needed that couple species population-community-ecosystem models with physiological process models for simulation of the response of ecosystems to rapid, large-scale changes in environmental factors.

(d) Theory and models of the interaction of ecology at the landscape to biome scale and meso-climate to regional climate need to be developed.

(e) Modeling the variability and heritability of biological traits is poorly developed; likewise, the adaptability of species and populations, especially to rapid changes, is not well understood.

(iii) *Prediction of Changes in Ecosystems and Natural Resources.* Requirements for improved predictive capability include:

(a) Methods and models to provide integrated assessment and prediction of yield of agricultural and forestry commodities (at both macro- and micro-economic scales) in the likelihood of a more variable climate in the future. While data may be available, analysis and model development are limited because resource, input use, management practice, and economic data are not linked.

(b) Models that simulate population, community, and ecosystem behavior, incorporate process understanding, and run over long time scales (centuries to millennia) are required in order to develop understanding of the feedbacks that ecosystem change will have on the physical and chemical environment.

(c) Model accuracy and precision are generally unknown. There is a continuing need to develop methods to evaluate model uncertainty and sensitivity—both for scientific prediction and use in the decision process.

(d) There is a shortage of biological oceanographers; systems, landscape, community, and population ecologists; and other biological scientists trained in numerical modeling, use of supercomputers, and ecological theory.

FY 1990 Agency Initiatives and/or Augmentations (Models)

(i) *Interdisciplinary Modeling.* Investigations associated with the Earth Observing System (Eos) have been initiated to utilize Eos and complementary data to improve the current predictive capabilities for such phenomena as ecosystem distribution, extent, and condition; nutrient cycling rates and fluxes, vegetation succession pathways, ecosystem energy balance, and water routing through ecosystems. Eos modeling activities will lead to more realistic mechanistic, linked, hierarchial models capable of operating at a variety of spatial and temporal scales. (Addresses weaknesses ii[c] and [d], and iii[b] and [c]; NASA: FY89=$0.5M, FY90=$0.7M.)

(ii) *Theoretical Ecology.* The theoretical ecology program at DOE is being developed to guide experiments and modeling in terrestrial environments. Of particular concern are theoretical considerations and descriptive functions governing atmosphere/landscape boundaries and the dynamics of particularly sensitive habitats, such as deserts and arctic regions. (Addresses weaknesses i, ii[a] and [b], iii[b] and [c]; DOE: FY89=$1.2M, FY90=$2.0M.)

(iii) *Models of Ecology-Climate Interactions.* Research will be conducted on the development of integrated models that link landscape-scale ecology and regional climate. (Addresses weakness ii[d]; EPA: FY89=$0, FY90=$0.5M)

(iv) *Modeling Climate Change Impacts on Terrestrial Ecosystems.* Research will be conducted to develop a predictive capability for estimating the potential effects of climate change on terrestrial ecosystems, both managed and unmanaged. Activities will include determining the sensitivity of natural resources to climate change and the effects of rapid climatic change on ecosystems, developing mesoscale models of forest ecosystem dynamics, analyzing how biogenic emissions are influenced by climate, and estimating the effects of global change on biodiversity. (Addresses weaknesses ii[a] to [d]; EPA: FY89=$0, FY90=$0.5M)

Earth System History

The Earth's geologic record provides a valuable source of information about past changes in climate, ecosystems, hydrologic conditions, and landscapes. The evidence of major variations in sea level, lake and ground water levels, extent of glacier ice and sea ice, changes in atmospheric composition, and dramatic changes in ecosystems in the past provide us with important insights into what the future may hold. The record of the past indicates that natural variability of the Earth's climate occurs over both short (decades to centuries) and long (millennia to millions of years) time periods. The natural variability of the Earth's climate can be deduced using a number of environmental indicators, including tree rings, glacier ice cores, fossils in terrestrial and marine sediment cores, annual layers in corals, geomorphic features, and sediment characteristics. Information about the causes, rates, and consequences of climate change can be extracted from the geologic record. Paleoclimatic data can also be used, within limitations, to test the ability of climate models to "predict" effects and dynamics of past climates. Paleoclimate data can thus improve the capability of models to predict future climate change.

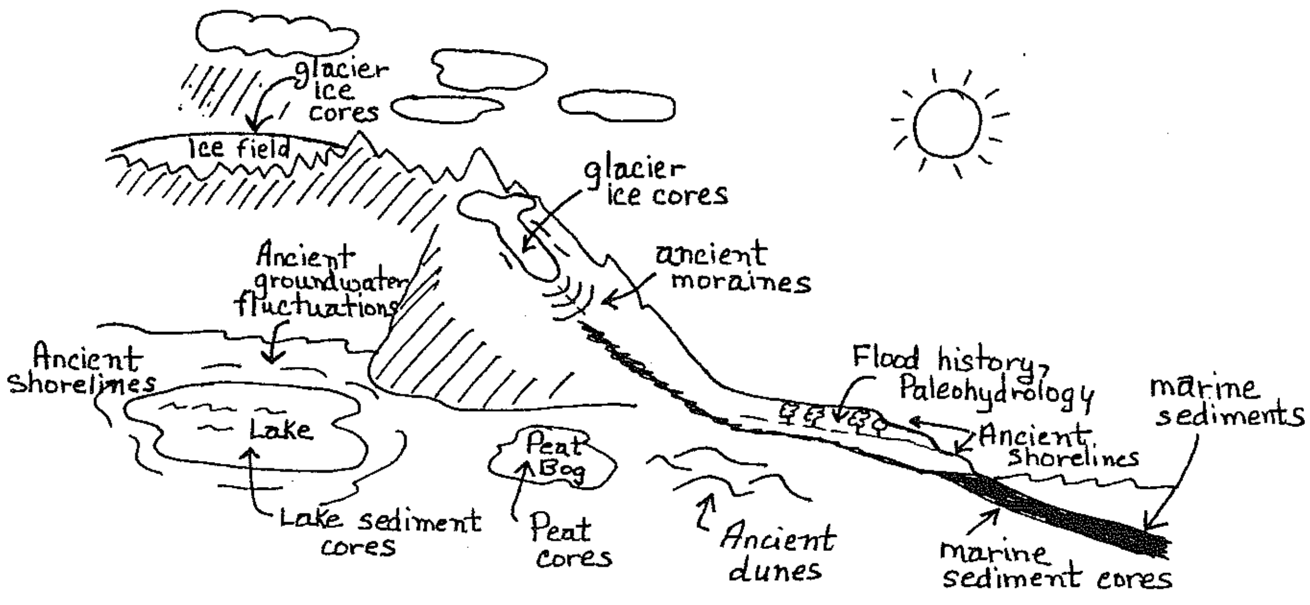


Figure 6. Schematic representation of some of the sources of paleoclimatic and paleoenvironmental records preserved in the geologic record.

The Earth System History element of the U.S. Global Change Research Program addresses several questions that are central to the problem of understanding global change. These are:

(1) What is the degree of natural variability in the global climate and environmental systems? In order to more fully discern the effects of human activity on global climate and environments, it is essential to improve understanding of natural variability of climate. The history of climate and environmental change is preserved in the Earth's geologic record. It behooves us to read the record and learn from it.

(2) What are the consequences of global change? The geologic record provides us with a rich source of information about the effects of past changes in climate and environments on short to long time scales, of local to global significance, and ranging from gradual changes to rapid, even catastrophic, rates of change. Our ability to anticipate future consequences of global change should be improved by examination of the evidence of past events and their consequences.

(3) What are the causes of global change? The geologic record of the past contains evidence that can be used to improve our understanding of the causes of climate change and other aspects of environmental change that act on short to long time scales.

(4) How can we test the predictions of the general circulation models and mesoscale climate models? The geologic record provides data about past global conditions that can be used to test "predictions" of the models based on past boundary conditions.

In order to understand global change from the perspective of the geologic record, it is necessary to develop three research components for this element: (1) long-term observations, (2) understanding Earth system history, and (3) developing predictive models.

Long-Term Observations. Reconstructing the history of Earth's climates and environments on both short and long time scales (decades to millions of years) provides an understanding of the full range of behavior of the global system and how it responds to change. It also provides a base line against which to measure future changes in climate and environments.

Understanding Earth System History. Research into past climate changes and environments provides insights into the rates of change under natural conditions, the consequences of climate change on the environment, and the natural variability of climate. It also provides evidence useful for understanding the causes of climate change.

Developing Predictive Models. Research on Earth system history contributes an important means of testing and improving general circulation models and mesoscale climate models. Compilations of paleo-environmental data can be used to develop synoptic reconstructions of past global environments for testing models.

Global-Scale, Long-Term Observations of Earth System History

Strengths of Current Observational Programs

(i) *History of the Oceans.* Methods have been developed to quantitatively describe physical (e.g., temperature) and chemical (e.g., carbon dioxide and nutrient) parameters of the oceans in the past. Methods include use of oxygen isotope variations in fossil foraminifers through time as an indicator of past temperature changes in the oceans, and use of fossil assemblages as paleo-environmental indicators. Current methodologies permit reconstruction of past ocean surface and deep water conditions on a global scale, on time scales of millennia to millions of years. Changes in sea levels and volumes of glacier ice can be approximated for the late Cenozoic. (NSF, USGS)

(ii) *Indicators of Past Climate Conditions.* Methods have been developed to use environmental indicators such as pollen and freshwater diatom and ostracode assemblages, tree rings, annual layers in corals, varves, and isotopic variations (e.g., oxygen, deuterium) to quantitatively reconstruct past terrestrial climates (e.g., temperature, precipitation). (NSF, USGS, DOE)

(iii) *Connecting the Past and Present.* Records of terrestrial climate, hydrologic, and oceanographic changes overlap man's historical and direct observational records of climate (surface temperatures and windfields) and hydrologic conditions (flood frequencies and magnitudes, fluctuations in groundwater, and drought frequency and duration). (USGS, NSF, NOAA)

(iv) *Reconstruction of Historical Fluctuations in Atmospheric Composition.* Gas samples from glacier ice cores provide unambiguous records of atmospheric composition over time scales of years to hundreds of thousands of years. Current instrumentation can accurately measure minor variations in radiatively important trace gases (e.g., carbon dioxide and methane) that are present in ice core gas samples. Thus, past natural variability in the composition of the atmosphere can be quantified and reconstructed over long time intervals. (USGS, NSF, DOE)

(v) *Permafrost Temperatures.* Capability now exists to accurately record temperature profiles in permafrost to discern evidence of warming temperatures at the ground surface during the past century. Model predictions suggest that global warming will be most severe at high latitudes, so monitoring permafrost temperatures can provide an early indication of the onset of warming. (USGS, NSF)

(vi) *Soil Maps.* Detailed soil maps of much of the United States now exist that show the location and extent of kinds of soils. Interpretations of the properties and patterns will indicate areas of similer Earth history. (USDA)

Weaknesses in Current Observational Programs and High Priority Research Needs

(i) *Global Change in High Latitudes.* General circulation models predict that a global warming of about 2 to 5 degrees C may occur during the next century as a result of projected increases in the atmospheric content of carbon dioxide. The models further suggest that the amount of warming may be significantly greater in high latitude regions than in lower latitudes, but the models do not agree well on the relative amount of warming to be expected at high latitudes. High latitudes may experience the earliest unambiguous onset of global warming from the "greenhouse effect." Because of the relative magnitude of environmental change at high latitudes, the past record of global changes in climates and environments may be most readily discernable in records from those regions. Long records of climate and environmental change from high latitude marine and terrestrial deposits would provide insights about the probable range of relative warming to be expected in those regions in comparison with sites at lower latitudes. High priority should be given to research aimed at reconstructing climate history of both land and sea in high latitude regions on both shorter (decades to centuries) and longer (millenia to millions of years) time scales.

(ii) *Environmental Parameters and the Fossil Record.* Reconstructing past climates and environments often depends in part upon knowledge of the environmental and climatic requirements of modern organisms that may be represented in the fossil record. However, the precise environmental requirements for many living organisms are poorly understood. Therefore, paleoclimatic reconstructions based on faunal or floral evidence preserved in the geologic record are often less precise than hypothetically possible. Research is needed to improve understanding of environmental parameters limiting the distribution, survival, and successful reproduction of organisms that may be represented in the fossil record.

(iii) *Time Resolution in Paleoclimate Records.* Many existing paleoclimate records lack adequate time resolution to permit detection of climate oscillations on the scale of decades or centuries, and most focus on the past 25,000 years or less. High priority research needs include improving the resolution of paleoclimatic records where appropriate, examining past rapid changes in the climate system, and studying time intervals prior to 25,000 years ago that may provide useful analogs for global warming or insights into the dynamics of the climate system.

(iv) *Paleoenvironmental records. In situ* observations and analyses of paleoenvironmental records from arid and semi-arid regions are insufficient to anticipate consequences of climate change. Priority should be given to expanding the network of monitoring stations and paleoclimate reconstructions in arid and semi-arid regions in order to improve understanding of the probable consequences of climate change.

(v) *Paleopedologic Interpretations.* Paleopedologic interpretations of the existing soil cover have not been systematically evaluated as a means of reconstructing historical spatial patterns of change.

FY 1990 Agency Initatives and/or Augmentations (Observations)

(i) *Permafrost and Ground Surface Temperature Measurement in the Arctic.* The USGS Climate Change Program will increase and diversify research on polar climates of the past as part of an augmentation for FY 1990. The geographic focus will be on Alaska and will include research on permafrost temperature profiles as a means of reconstructing ground surface temperature changes during recent decades to centuries. This will also provide a basis for monitoring present and future ground temperatures in permafrost at the well sites over time. The Program will also support research on late Cenozoic paleoclimates in Alaska. (Addresses weakness i; USGS: FY89=$0.1M, FY90=$0.4M.)

(ii) *Climate of Arid Regions.* Research on past and present climates of arid regions of the United States will be supported by the USGS Climate Change Program. This will include research related to desertification and climate change of the present and the past. (Addresses weakness vi; USGS: FY89=$0, FY90=$0.2M.)

Improving the Understanding of Earth System History Processes

Strengths of Current Understanding

(i) *The Climate Record.* The geologic record provides a rich source of information about past and present geologic processes, environments, catastrophic events, and the history of biospheric response to climate and other environmental changes. Examples include evidence for changing rates of sedimentation or erosion, ecosystem changes in reponse to volcanic ashfalls, and changes in the dust content and gas composition of glacier ice. Many types of data can be compiled to recreate a "snapshot" of global or regional conditions at selected times in the past under different climate regimes.

(ii) *Causes of Climate Change.* Although much of the variability in climate records on time-scales of decades to millions of years is not well understood, progress is being made in discovering the causes of climate change, particularly on time scales of tens of thousands to hundreds of thousands of years. Predictable variations in the orbital parameters of the Earth are now recognized as a significant forcing influence on the Earth's climate.

Weaknesses in Current Understanding and High Priority Research Needs

(i) *Ocean Chemistry of the Past.* Paleoenvironmental indicators of some aspects of ocean chemistry (e.g., alkalinity) are poorly developed. High priority should be given to efforts to improve abilities to reconstruct past ocean chemistry and other oceanographic parameters.

(ii) *Record Dating Capabilities.* Dating terrestrial records beyond the limit of radiocarbon dating (ca. 40,000 yrs) is difficult, and there are also problems with chronological control of marine records. Methods other than radiocarbon dating need to be developed and perfected if possible; several approaches show promise (e.g., thermoluminescence dating and strontium isotope dating).

(iii) *Ice Core/Trace Gases.* The extent of melting in glacier ice and the effects of melting on gas concentrations in ice cores has not been adequately addressed. Priority should be given to research focusing on this problem.

(iv) *Linkages Between Oceanic, Atmospheric, and Lithospheric Processes.* Linkages of processes between different elements of the Earth system are in many cases poorly understood. Comparisons between aeolian components (e.g., desert dust and volcanic ash) in glacier ice cores and nearby sediment cores should be analyzed to provide a sound stratigraphic correlation between the two types of records. This will improve understanding of linkages between the major Earth systems.

(v) *Climate-Geological Processes Relationships.* Relationships between climate variation and rates and intensity of geologic processes in arid and semi-arid environments are poorly understood. Desert and semi-desert environments are likely to change in extent and character as a result of climate change. Priority should be given to research and monitoring efforts that focus on desert processes and climates of the past and present.

(vi) *Ecosystem-Climate Relationships.* How ecosystems and environments respond to climate change is inadequately understood, limiting ability to fully anticipate responses to future climate change. High priority should be given to examining evidence in the geologic record for the type, rate, and frequency of climate changes and the environmental responses to those changes. Research should be carried out on a variety of time scales, from decades to millions of years.

(vii) *Abrupt Climate Change.* Detailed global or regional records of rapid climatic events are inadequate. Projections of future global change include unprecedented rapid warming. There are analogs of abrupt climate change in the geological record (e.g., Younger Dryas, Little Ice Age), but we have insufficient understanding of their causes and of the interactions and response of the climate system to these rapid events.

(viii) *Ice Coring Capabilities.* A more complete analysis of climate and the history of atmospheric composition requires obtaining glacier ice cores from all possible latitudes where glaciers exist. Ice cores provide many types of paleoclimatic and paleoenvironmental data. Greater resources should be devoted to expanding the U.S. research and development effort to improve ice coring methods to obtain longer ice cores and provide high resolution analysis of glacier ice cores from all possible latitudes

FY 1990 Agency Initiatives and/or Augmentations (Understanding)

(i) *Sediment Coring Project.* A terrestrial sediment-coring project utilizing mechanical core drilling methods will be initiated in FY 1990 by the USGS Climate Change Program. The initial geographic focus of the drilling project will be high latitude North America. The objective is to obtain long, continuous-as-possible records of climatic and environmental changes from high latitude spanning intervals up to several millions of years. This project will be conducted jointly with the Geological Survey of Canada. (Addresses weaknesses vi and vii; USGS: FY89=$0, FY90=$0.3M.)

(ii) *Changes in Earth History.* Under the new element at NSF, Changes in Earth History, the geologic record will be used to help understand past environmental changes of global scope and the processes that govern environmental change. (Addresses weaknesses vi and vii; NSF: FY89=$0, FY90=$0.7M.)

(iii) *The Second Greenland Ice Sheet Project (GISP II).* NSF will increase emphasis on the recovery of paleoclimate and atmospheric chemistry data in ice cores from Greenland. (Addresses weaknesses iv and viii; NSF: FY89=$2.0M, FY90=$4.0M.)

(iv) *Paleohydrology Studies of the Great Basin and Southwest.* The USGS Water Resources Division (WRD) will increase emphasis on paleohydrologic studies of the Great Basin and Southwest to reconstruct paleoclimates (with an emphasis on pluvial lakes) of the late Pleistocene and Holocene and groundwater flow histories as preserved in calcite deposits in arid basins. (Addresses weaknesses v and vi; USGS: FY89=$0.3M, FY90=$0.5M.)

(v) *High Resolution Paleoceanographic and Paleoclimatic Records.* USGS Climate Change Program Geologic Division (GD) will begin a new research effort aimed at obtaining high-resolution records of paleoceanographic and paleoclimatic history preserved in corals, which are particularly well-suited for studies of climatic variability over time spans of several centuries, but with an annual temporal resolution comparable to tree rings. (Addresses weaknesses i and iv; USGS: FY89=$0, FY90=$0.3M.)

(vi) *Paleoceanographic Conditions from Marine Sediments.* New research aimed at improved understanding of paleoceanographic conditions from evidence preserved in marine sediment cores will be supported by the USGS Climate Change Program in FY 1990. (Addresseses weakness i, iv, v and vi; USGS: FY89=$0, FY90=$0.4M.)

Developing Predictive Models

Strengths of Current Models

(i) *Global Circulation Models.* Experience shows that paleoenvironmental data sets provide a valuable means of testing and improving global circulation models. Paleoclimate data, particularly for the past (ca. 25,000 years) have been compiled over the past several decades, providing an important foundation upon which to build future global-scale synoptic reconstructions for model testing.

Weaknesses in Current Models and High Priority Research Needs

(i) *Paleoclimate Data.* Most existing paleoclimate data sets focus on the past 25,000 years or less of Earth history. Data sets for earlier periods must be developed to provide suitable analogs for substantial global warming in order to test the predictive powers of climate models.

(ii) *Ice-Flow Models.* Glacier ice-flow models are currently inadequate to provide accurate chronologies for ice cores. Development of improved ice-flow models is an important priority to enhance results of ice-core paleoclimate studies.

(iii) *Climate Models.* Current climate models generally agree that the climate change is likely to be most dramatic at high latitudes. The models differ substantially on the magnitude and regional distribution of climate change at high latitudes. A high priority for research is refinement of the climate models to reduce the range of uncertainty in the predictions of high latitude climate change. Coupled with this is the need to acquire additional paleoclimate data sets from high latitudes (both marine and non-marine), on a variety of time scales (centuries to millions of years) to help resolve differences between climate model predictions.

(iv) *Global Circulation Models.* The ability of current GCMs to reproduce rapid changes in the state of the climate system has not been adequately tested. Geological records of rapid change in climate are not sufficiently detailed to provide initial conditions for the models or to test the model results.

(v) *Soil Formation Models.* Models of soil formation and their distribution remain qualitative rather than predictive and quantitative. The linkages would provide a means to integrate soil cover with other global data sets.

FY 1990 Agency Initiatives and/or Augmentations (Models)

(i) *Analogs for Predicted Future Global Warming.* The USGS will expand research aimed at developing a synoptic reconstruction of a significantly warmer-than-present interval during the Pliocene (2.6 to 3.0 million years ago). This will be an augmentation of the USGS Climate Change Program. Pliocene warm intervals should provide important analogs for global warming of the magnitude predicted for the next century. The Pliocene paleoclimate data will be used to develop a variation of an existing General Circulation Model in cooperation with one of the modeling research centers. (Addresses weaknesses i and iii; USGS: FY89=$0.8M, FY90=$1.1M.)

Human Interactions

Human activity is a critical element in global change both in terms of initiating processes of change in the environment and altering ongoing processes. Fundamental research on the human dimensions of global environmental change is necessary to understand patterns of (1) direct human action or impact on the environment, and (2) the indirect structural and institutional causes of change in the Earth system, including such factors as economic markets, national legal and regulatory systems, and social and economic aspirations in developing nations.

Research on anthropogenic forces in global change will provide the necessary scientific foundation for public policy studies to be conducted outside the global change research initiative. These policy studies may address the response of human institutions to global change in terms of both mitigation strategies and processes of adaptation.

Most environmental problems are directly caused by human action or are exacerbated by human activities. Included among these are the following:

- *"Greenhouse" Warming.* Increasing atmospheric gas concentrations resulting from human population settlements, fossil fuel consumption, agricultural practices, and industrial emissions.

- *Acid Deposition.* Acidification of soil and water supplies resulting from atmospheric pollution by industry and fossil fuel consumption.

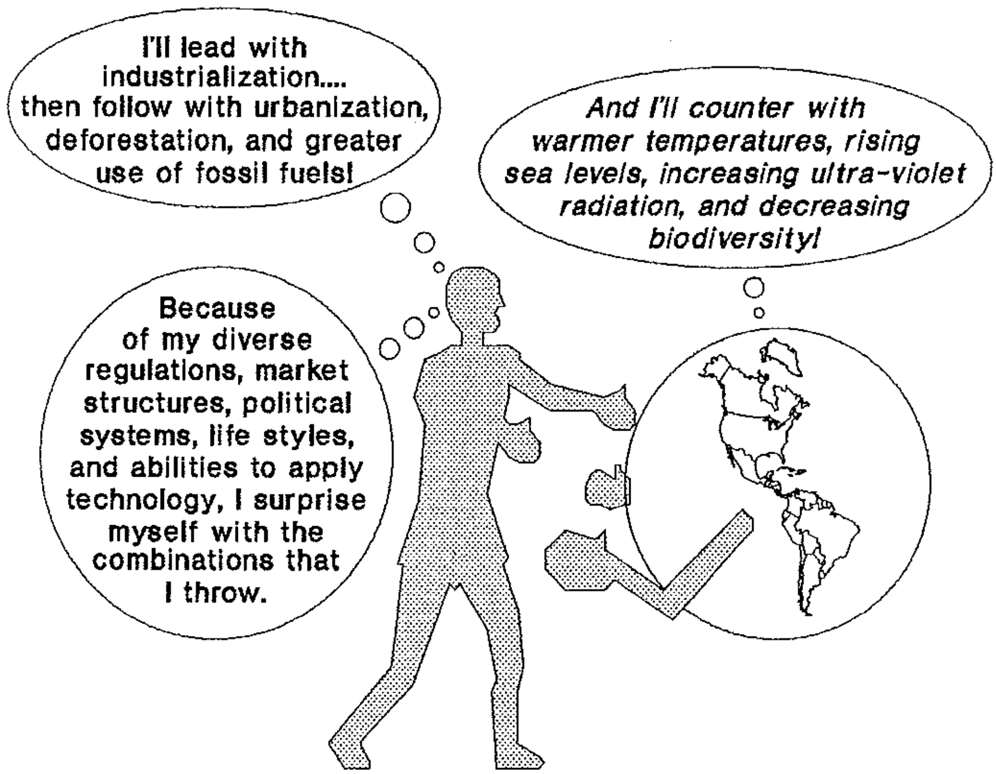


Figure 7. Representation of the impact of human activities on the global environment.

- *Deforestation.* Human removal of forests in temperate regions over the past 2,000 years and contemporary conversion of tropical forests to other land uses.
- *Biodiversity.* Displacement and possible loss of plant and animal species through agricultural and urban expansion.
- *Erosion.* Removal of fertile topsoil by water and wind throughout the world by agricultural practices and settlement patterns.

Understanding the role of human dimensions in global environmental change requires fundamental research on human social, economic, and institutional behavior. The research task has three components: (1) data base development, (2) understanding processes of change, and (3) modeling processes of human interactions with the environment.

Data Base Development. Empirical research on the human dimensions of global change will be dependent upon the establishment of comparable, cross-national data bases that are maintained over long periods of time. These data bases should encompass human activities such as land use practices, fossil fuel consumption, and industrial emissions. There should also be data bases that track changes in public attitudes and perceptions of risk in the environment and data on population distribution and consumption patterns. The discussion of monitoring systems here focuses on data collection within the United States. An important set of tasks at the present time consists of identifying comparable data bases in other nations, standardizing measurement instruments, and developing cross-national models that link human activities and environmental change.

Understanding Processes of Change. As suggested in Figure 7, research on processes of change should deal with both direct human action and indirect social, structural, and institutional influences on global change. Among the very important indirect influences are legal and regulatory systems that foster particular types of environmental behaviors, economic markets and pricing practices that can encourage or discourage environmentally sound behaviors, and international trade and investment policies. Past and present patterns of industrial production and transportation and the enduring chemical residues of both must also be understood. Cultural differences in institutions and behavior and culturally influenced responses to global change and environmental risk should be better understood.

Modeling Processes of Human Interactions with the Environment. Ultimately, social and economic data and understandings of (1) processes of social and economic change, (2) environmentally significant human action, and (3) human elements in physical and biological processes of global change must be integrated in predictive models. Such models, operating under the assumption of similar conditions, will link past patterns of behavior with scenarios for the future. At the present time, current trends cannot be projected reliably into the future for two reasons. First, the pace and nature of environmentally critical human activities are not well understood, and second, these activities change over time, in part as a result of efforts to moderate the human impacts of global change.

The following sections provide information on the strengths and weaknesses of current research on the human interactions in global change and discuss research that will be supported under the U.S. Global Change Research Program in its FY 1990 increment. Research described below is intended to provide a scientific understanding of the role of human interactions in global change. It is not intended to develop policies for dealing with global change.

Global-Scale, Long-Term Observations of Human Interactions

Strengths of Current Observational Programs

(i) *Maps and Digitized Spatial Data.* National map and digital data on basic land surface information are available; population and economic data from the 1990 census will be integrated into these maps and made available in Geographic Information Systems (GIS) format in the early 1990s. (USGS, Census) Increasingly sophisticated GIS capability is available for the integration of demographic, economic, physical, and biological elements in space. (NSF)

(ii) *Land Use Data.* Continuous photographic data on land use in the United States are available from the 1930s to the present (USGS); historic satellite data and recent field, aircraft, and satellite data are available to examine the influence of demographic pressures on deserts and tropical forests. (NASA); Periodic inventories of land use and condition are obtained by site visits for most U.S. lands. (USDA)

(iii) *Survey Data.* Annual surveys are conducted of public attitudes and perceptions that can be used to provide data on public responses to environmental changes. (NSF)

(iv) *Data on Natural Processes Affected by Human Action.* Data on water quality, acid deposition, tropical deforestation, and desertification show the combined effects of natural and anthropogenic causes of change. Estimates of the spatial-temporal relationship between acid precursor emissions and acid deposition have been developed. (USGS, NASA, EPA, DOE)

(v) *Data on Energy Transformations.* Data are assembled on energy production and use, and data for global fossil fuel CO_2 emissions by fuel type and region are available over the period 1966 to the present. Data on the emission of non-fossil fuel "greenhouse" gases (CO_2, CH_4, N_2O) and from human activities such as agriculture, land-use change, energy production and use, and manufacturing are also available for individual years. (DOE, EPA)

(vi) *Chlorofluorocarbon Data.* Estimates of chlorofluorocarbon production by country are available. (DOE)

Weaknesses in Current Observational Programs and High Priority Research Needs

(i) *Data Collection and Standardization.* More environmental questions should be included in ongoing surveys. New surveys of environmental perceptions and behaviors in the United States, standardized with social surveys in other nations, are needed. Long-term comparable, cross-national data bases that combine institutional and governmental responses to global change must be established.

(ii) *Methodological Research.* National level data, mostly based on samples of the population, must be reconciled with non-sampling data to provide complete coverage of small areas. A framework that permits analysis to move between large samples and small areal data bases is needed.

(iii) *Land Use and "Greenhouse" Gases.* The effects of human behavior on the environment must be examined for long time periods to improve the measurement and prediction of the production of "greenhouse" gases. Most data on land use practices and demographic impacts on land use are recent and only available for short time periods. To make accurate estimates of the cumulative effects of land use on the production of "greenhouse" gases, data on historical patterns of land use in specifically defined areas are essential. Parallel data sets with information on land use patterns in other parts of the world must be identified.

(iv) *Other Gases.* Measurements of fossil fuel CO_2 do not yet provide adequate information regarding the uses to which energy is put outside the United States. Uncertainty surrounding current estimates of emissions from non-fossil fuel CO_2 is unacceptably great. Measurements of the escape rate of cholorofluorocarbons into the atmosphere are inadequate. Emissions data on a number of radiatively important trace gases, especially CH_4 and N_2O, for a number of industrial and agricultural sources are inadequate.

(v) *Human Influences on Ecosystem Change.* Anthropogenic causes of ecosystem changes must be disentangled to the extent possible from natural causes of change, as reflected in a wide spectrum of data, e.g., data on water quality, acid deposition, deforestation, and desertification.

(vi) *Agricultural Links to Resource Availability and Quality.* Crop production decisions, input use, and cropping practices must be linked to dates on resource availability and quality. For example, explicit linkages between data on crop production and practices and agroclimate zones, water availability and water quality must be made.

FY 1990 Agency Initiatives and/or Augmentations (Observations)

(i) *Land Surface Data Systems.* Provide for permanent archiving, management, access, and distribution of land Earth-science data sets for global change research on the interaction between human activities and environmental processes. This includes transfer of remotely sensed data (e.g., Landsat) to stable storage media, archive of selected USGS data sets for global change, and access to land data maintained by other Federal agencies. (Addresses weaknesses i to v; USGS: FY89=$0, FY90=$1.5M. [This new $1.5M initiative will replace a $0.5M research program to yield a budget augmentation of $1.0M.])

(ii) *Improvement of Social Data Systems.* Data resources dealing with individual and institutional actions affecting environmental changes, including research on measurement and methodological issues, must be improved. Collection instruments for international data bases on the social and economic dimensions of global environmental change must be standardized. (Addresses weaknesses i and ii; NSF: FY90 reprogramming=$0.2M.)

Improving the Understanding of Human Interactions

Strengths of Current Understanding

(i) *Fundamental Social Research.* Research on anthropogenic causes of Earth system processes is directly dependent on a strong research base of fundamental understandings of demographic, social, economic, and political behavior and processes. (NSF)

(ii) *Strengths of Demographic Research.* Demographic pressures—the sheer size of the human population and its distribution—are a major cause of global change. Demographers can predict population growth and the effects of migration and changing age distributions in the population with great accuracy. (NIH, NSF)

(iii) *Research on Risk Perception and Communication.* Response to global environmental change is directly related to individual and societal attitudes to risks. Risk perception and risk aversion vary by individual and across social groups. A growing body of research is assessing the relationship between the way risks are communicated to the public and subsequent behavior, including receptivity to change. (NSF, EPA)

(iv) *Regulatory Studies.* Valuable research is being conducted on the effects of regulation on economic behavior and market performance. In addition, studies exist of the role of regulation in changing certain types of human behavior. (NSF)

(v) *Land Surface and Geographic Processes.* Research is conducted on the interactions between human activities and natural processes by inventorying vegetation and land-use changes and determining environmental impacts. This research involves integrating remotely sensed data and Earth-science data for applications such as vegetation monitoring as an indicator of cultural impacts. (USGS, NASA, USDA)

(vi) *Information on Emissions of Gases.* Demographic studies can be used to estimate future emissions of radiatively active trace gases. Moreover, preliminary data and information exist on the relationships between human activities and emissions of "greenhouse" gases. (EPA)

Weaknesses in Current Understanding and High Priority Research Needs

(i) *Identification of the Ways That Human Activities Affect Global Change.* Research should focus both on specific types of human activities responsible for global change and on the interrelationships among these activities. This would include research on such topics as the relationships between economic growth, energy efficiency, and land use changes. It would also include research on the connections between human activities and emissions of natural and industrial origin.

(ii) *Multiple Threats to the Environment.* Research is needed on interacting physical, natural, and human causes of environmental transformation or "syndromes" of environmental change, such as threats to forests posed by changes in land allocation and forestry practices, climate, and atmospheric chemistry. Studies of anthropogenic processes of change in the environment have focused on the impacts of individual behaviors (such as fossil fuel consumption) or on particular environmental problems (like deforestation or acid deposition). This narrow problem-by-problem formulation must be augmented by integrated research on the broad spectrum of the causes of environmental changes. This should also include research on the environmental consequences of contemporary patterns of national and regional social and economic development, political and regulatory responses to global change, and cultural differences in environmental degradation.

(iii) *Human Health Effects of Global Change.* Global climate change will affect disease patterns and pest infestations. Increased UV-B exposure will seriously affect human health, behavior, and food supplies. Research is also needed on behavioral aspects of health in a changing global climate. This would examine the connections between individual and public recognition of the consequences of dangerous behaviors and between government regulation and changes in behavior.

(iv) *Environmental Risk.* Although there has been a great deal of research on this topic, most of it has not dealt with issues related to global change. Research is needed on cultural and institutional influences on risk aversion and on reactions to uncertainly in the environment. In particular, little systematic research has been done on the response to large-scale, high-consequence events such as global change, climate change, or specific events like oil spills.

(v) *Human Effects on Water Resources.* Research is needed on processes by which human activities affect water resources, including changes in ambient water quality, groundwater levels, coastlines, and estuaries.

(vi) *Legal Issues.* Research is needed on the effects of national and international laws and agreements on environmental change and on the relationship between governmental controls and market mechanisms in environmental degradation. Research is also needed on the implementation of regulatory policies and national and international compliance.

(vii) *Trade and Investment Practices.* There is a need for research on the nature of trade and investment practices in global change and their influence in both developed and developing countries. Similarly, the relationship between national and international commodity pricing regimes and debt repayment rules and national agricultural, forestry, and water policies should be examined.

FY 1990 Agency Initiatives and/or Augmentations (Understanding)

Basic Social and Behavioral Science Research. Fundamental research on the relationships among global environmental change and human activities, including social, economic, political, legal, and institutional processes. (Addresses weaknesses i, ii, and vi; NSF: FY90 reprogramming=$1.0M.)

Developing Predictive Models

Strengths of Current Models

(i) *Research Conducted During the Energy Crisis.* The energy crisis of the early 1970s stimulated a great deal of research on fossil fuel consumption. It provided a research base on means of changing consumption patterns (e.g., the importance of shifts in economic incentives and disincentives to behavioral change). At that time, scenarios for anticipated changes in supply and demand of energy sources also were developed. (DOE, EPA)

(ii) *Research on Economic Markets and the Environment.* There is a body of research on the dynamics of economic markets. Economic markets can be an efficient means of allocating resources when prices reflect all costs. But since current market mechanisms do not systematically consider environmental costs, they tend to promote behaviors that exacerbate global change, such as the excessive use of fossil fuels. Both national and international markets are distorted by government interventions reflecting national, but not necessarily environmental, interests. (NSF)
(iii) *"Greenhouse" Gas Models.* A first-generation set of models to assess the relationship between human activities and "greenhouse" gas emissions has been developed. (DOE)

(iv) *Models of Current and Future Emissions.* Models exist to estimate current and future United States emissions of NOx, SOx, and volatile organic carbon and particulate matter to a relatively high degree of spatial and temporal resolution. These can also be used to estimate CO and CO_2 emissions in the United States. (EPA)

(v) *Models for Understanding Human Interactions in Global Change.* Population, energy, agriculture, forestry, and economic models relevant to global change are available. These can be used to help anticipate changes in international trade, market areas, service centers, settlement patterns, transportation systems, and the uses of energy and water resources caused by climate-induced shifts in agricultural zones. (NSF, USDA, DOE)

Weaknesses in Current Models and High Priority Research Needs

(i) *Long-Term Models of Human Dimensions of Global Change.* Credible models for long-term changes in human activities that affect environmental change and, conversely, models of the effects of long-term environmental changes on human activities must be developed.

(ii) *Economic Forecasting in the Medium Term.* Economic forecasters now possess the technical and computational tools for developing the medium-term models (5 to 10 years) needed for the study of global change on these time scales. The achievement of the requisite reliability in forecasting, however, will entail a major program to eliminate existing gaps in the data and to resolve a range of conceptual issues.

(iii) *Population Models.* Models of population migration and growth must be integrated with agricultural production and economic development models to understand food and shelter needs under conditions of shifting climate conditions.

(iv) *Models Linking Local Activities to Global Change.* Human activities undertaken in response to local conditions can have an unforeseen global impact. Research is needed on the links of local and regional activities to global change.

(v) *Contrasts between Developed and Developing Countries.* Models are needed of the effects of regional economic and agricultural changes, particularly those caused by global environmental change, on national economies. As part of this research, global models of resource and commodity trading and an inventory of energy needs and potential for conservation are required.

(vi) *Second Generation of Emissions Models.* A second generation of models of "greenhouse" gases and energy emissions is needed. These models should permit the analysis of the interaction of human activities and explicit technological alternatives.

FY 1990 Agency Initiatives and/or Augmentations (Models)

(i) *Models of Human Interactions in Global Change.* Initial methodological and substantive research to develop more sophisticated models of human and institutional interactions in global change will be undertaken. (Addresses weaknesses i, ii, iii, iv, and v; NSF: FY90 reprogramming=$0.2M.)

Solid Earth Processes

One of the tenets of the geological sciences is that the present is the key to the past. In the context of global change, however, the present is the key both to deciphering the past geologic record and to achieving a better understanding of those solid Earth processes that affect the life-supporting characteristics of the global environment, especially those processes that are active at the interfaces between the Earth's surface (subaerial and submarine) and the atmosphere, hydrosphere, cryosphere, and biosphere. Such studies include: (1) subaerial and submarine effusive and explosive volcanism, including emission of various radiatively important gases, as a contributor to and perturbator of the composition of the atmosphere and the hydrosphere (oceans); (2) surficial and near-surface processes that produce changes on the land, in the oceans, and in the atmosphere, such as aeolian erosion, transport and deposition of sediment (including dust), and desertification (natural and human-induced); (3) coastal erosion resulting from rising sea level, natural or human-induced subsidence, and changes in volume of fluvial sediments transported to the oceans; and (4) changes in the areal distribution and rheology of glaciers (in response to climate change) and the effect of the neotectonic history of Antarctica on ice sheet growth and decay. Tectonic activity is included as it relates to such processes as volcanism and near-surface or surface crustal deformation, which result from the loading of the Earth's crust by glaciers.

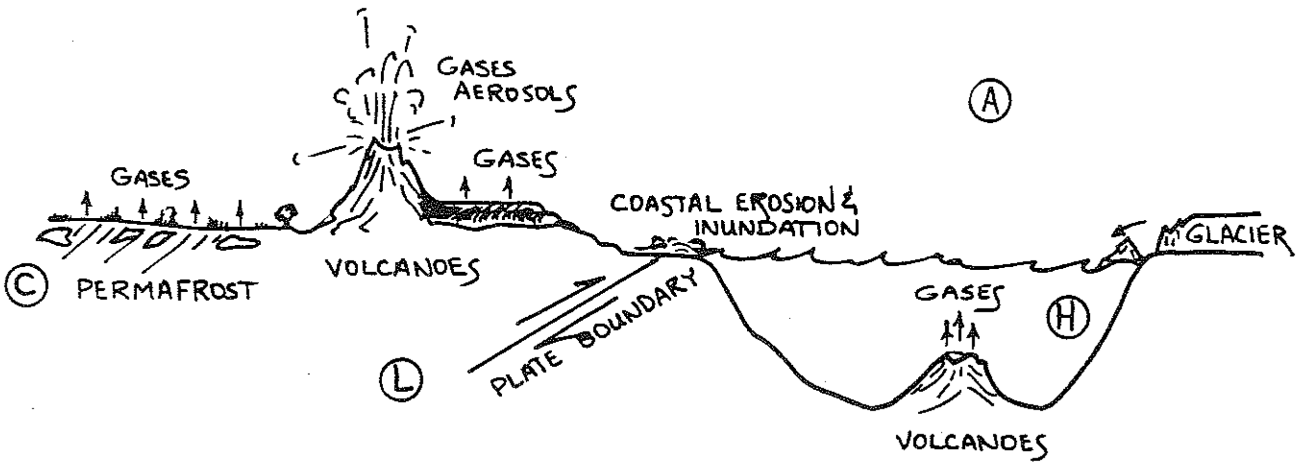


Figure 8. Schematic representation of solid Earth processes active at various interfaces of the geosphere: subaerial and submarine volcanism, coastal erosion and inundation, glaciers, permafrost, and crustal motion. Elements of the geosphere are shown with letters: A, atmosphere; C, cryosphere; H, hydrosphere; and L, lithosphere.

In the context of the U.S. Global Change Research Program, six geologic processes have been initially determined to be most important in causing changes or resulting from changes in one or more elements of the geosphere and biosphere:

- *Volcanism*. Subaerial and submarine explosive and/or effusive volcanism that emits a variety of radiatively important gases that contribute to or perturb the composition of the atmosphere and the hydrosphere (oceans).

- *Coastal Erosion and Inundation*. Resulting from rising sea level, natural or human-induced subsidence, or changes in volume of fluvial sediments transported to the oceans.

- *Glacier fluctuation*. Changes in the area, volume, and rheology of glacier ice on land (in response to climate change) and, also, the effect of the neotectonic history of the land on ice sheet growth and decay.

- *Permanently Frozen Ground (Permafrost)*. Changes in the areal extent of discontinuous and continuous permafrost and release of radiatively important gases to the atmosphere as frozen ground melts. Decomposition of marine gas hydrates also will release radiatively important gases to the ocean and atmosphere.

- *Surficial Processes*. The erosion, transport, and deposition of sediment, resulting in such events as dust storms and the process contributing to desertification.

- *Crustal Motion*. Frequency and magnitude of earthquakes in populated areas and magnitude, both past and present, of tectonic uplift or subsidence in coastal areas. These data are necessary to establish local vs. global absolute sea level change.

In order to provide needed scientific input to policy decisions associated with global change, three research components of key solid Earth processes must be understood: (1) Long-term observations, (2) processes studies, and (3) conceptual picture, models, and prediction.

Long-Term Observations. For most geologic processes relevant to global change, there is a very great need to initiate new, as well as to continue, ongoing global observations from ground-based observations and remote sensing platforms (airborne and/or satellite), so that reliable baselines for key parameters can be established against which future (or past) changes can be compared. The existing global network of observatories can record scientific data on only a small number of the world's active land volcanos. Little data exist for the 80 percent of global volcanism that is underwater. The global seismic network also needs to be expanded to cover areas not now covered by seismological observatories. A seismic network will provide proxy data on volcanism on the 70 percent of the Earth surface covered by water. Long-term observatories need to be established on submarine volcanos. The crustal dynamics project, with its network of very long baseline interferometry (VLBI), satellite laser ranging (SLR), and global positioning system (GPS) station network, should continue to monitor plate motion and fault activity, and should be expanded to cover potentially hazardous regions. The Landsat series of satellites must be continued, even during the Earth Observing System (Eos) era, to provide a global record of changes in glacier area and changes in coastal regions (shoreline position and configuration) over time.

Process Studies. The frequency, magnitude, and geographic occurrence of explosive volcanism need to be better understood using the historic and geologic record (see the section on Earth System

History). Studies must include the nature of the eruptive products, their resident time in the atmosphere, and their effects on climate (see the section on Climate and Hydrologic Systems). Submarine volcanism and its effect on the chemical and mass balance of the oceans, especially processes active on mid-ocean ridges, need to be understood better. The globe circling ocean ridge system contributes a flux of heat, volatiles, fluids, and particulates into the ocean. These contributions may well influence ocean circulation, chemistry and the CO_2 budget. Acoustic imaging systems, use of data from sea-beam technology for precise bathymetric contour maps, and direct observation and sampling by manned and unmanned submersibles can provide some of the needed data.

Coastal erosion and inundation studies need to be broadened and conducted in association with calibrated tide-gauge investigations, like the Global Positioning System (GPS) and Very Long Baseline Interferometry (VLBI), to correlate sea level rise with erosion and inundation. Considerably more effort needs to be directed at achieving a better understanding of the Greenland and antarctic ice sheets, which contain 99.3 percent of the world's volume of glacier ice. Of particular importance is the long-term stability of the West Antarctic ice sheet because its disintegration would cause a rise of 6-8 meters in sea level. (See the section on Climate and Hydrologic Systems.)

Landsat images, future satellite altimetry (laser and radar), and airborne radio-echosounding surveys are needed for studies of changes in the area and volume of theantarctic and Greenland ice sheets. Permafrost is particularly sensitive to climate warming. In addition to expanding field and theoretical studies of the effect of climate warming on temperature profiles in permafrost, studies of gas release from melting permafrost are needed (see the section on Biogeochemical Dynamics). An expanded network of digital seismometers for the Global Seismic Network is needed to advance our knowledge of data, origin time, location, depth, and magnitude of earthquakes on a global basis and provide proxy indicators of submarine volcanism. High-quality GPS data need to be acquired for a variety of crustal motion studies.

Conceptual Picture, Models, and Prediction. In 1815 the explosive eruption of the Tambora volcano in Indonesia depressed the global mean annual temperature by several degrees C. for several years. The ash fall also destroyed crops and deposited new soil material. The impact of a similar eruption on modern agricultural production in temperate and high latitude growing areas would be severe. Volcanologists need to work with climate modelers (see the section on Climate and Hydrologic Systems) to develop global circulation models that can accurately predict the consequences of a large explosive volcanic eruption on global climate. Moreover, submarine volcanic eruptions, emanations, and hydrothermal circulation affect the chemical mass balance of the oceans.

Interactive models also need to be developed that relate global climate warming to changes in volume of glacier ice which, in turn, lead to changes in volume of the ocean component of the hydrosphere. The magnitude and rate of sea level changes during the next several decades to centuries must be predicted to enable the critical economic decisions related to erosion and inundation of low-lying coastal regions and the impact on property and structures. Better models of crustal deformation are needed to achieve the goal of predicting time, location, and magnitude of earthquakes and uplift or depression of land in heavily populated regions because of the economic consequences of such events.

Global-Scale, Long-Term Observations of Solid Earth Processes

Strengths of Current Observational Programs

(i) *Volcanism.* Global observation of subaerial volcanic activity, both explosive and effusive, is performed by a network of ground observers. Meteorological satellites and total ozone measuring satellites (TOMS) have been used to monitor the dispersal into the troposphere and stratosphere of tephra, gases, and aerosols from explosive volcanic activity. Landsat-type satellites record new patterns of tephra deposition on land and new areas of lava flows.

(ii) *Coastal Erosion and Inundation.* Approximately 70 percent of the easily erodible coasts of the continents is known to be eroding. Research projects to study coastal erosion and inundation in response to rising sea level are underway in several coastal areas.

(iii) *Permafrost.* The distribution of continuous and discontinuous permafrost in the Arctic is relatively well known.

(iv) *Crustal Motion.* A global seismic network (GSN) measures and monitors earthquake activity. Global positioning system (GPS) receivers are available to make use of the DOD NAVSTAR satellite constellation. GPS and other geodetic techniques measure global tectonic movements, thereby providing direct confirmation and measurement of processes associated with plate tectonics. The measurements also contribute to earthquake and volcanic eruption predictions.

Weaknesses in Current Observational Programs and High Priority Research Needs

(i) V*olcanism.* It has been estimated that 80% of the Earth's volcanic activity is submarine. The magnitude, frequency, geographic distribution, quality, and character of eruptive products and emissions from submarine volcanos is poorly known. A major improvement in our knowledge of the geographic distribution, magnitude, and frequency of submarine volcanic activity is needed. A systematic survey program of the ocean floor with acoustic imaging systems, beginning with the mid-ocean ridges, is required as the first step. We know that a significant but undetermined quantity of heat and materials are transmitted to the ocean from the solid Earth via the global ocean ridge crest system, which must have important, but as yet unquantified, effects on the role of ocean circulation, heat transport, ocean ecosystems and ocean/atmosphere interactions controlling climate. The RIDGE program (whose planning has been supported by NSF, NOAA, USGS and ONR) has developed a science plan to address these issues.

(ii) *Coastal Erosion and Inundation.* A Landsat-type global observing system is needed to document areal changes in barrier islands, wet lands, and low-lying coastal areas on a global basis, especially in heavily populated regions most susceptible to rising sea levels related to melting of glacier ice. A long-term record of coastal change at key coasts must be compiled to provide baseline information against which future change can be measured.

(iii) *Permafrost.* The rate of retreat of the edge of discontinuous permafrost is not well known. The reduction in area of discontinuous permafrost is related to climate warming; hence, a network of observatory boreholes in cold continuous permafrost and monitoring of areal change in discontinuous permafrost are needed to assess the impact of global climate warming in the Arctic.

(iv) *Crustal Motion.* The number of stations in the GSN is insufficient to cover the Earth adequately and monitor it with the precision necessary for understanding active crustal processes. Numbers of GPS instruments are insufficient to meet scientific demands for the monitoring such instruments provide; all of the plate boundaries, active faults, and volcanos that should be monitored to truly define global tectonic change. Seismicity is the harbinger of volcanic activity on land and a proxy indicator of volcanism on the sea floor. No accurate global geoid model exists; a model could be constructed from satellite gravity measurements.

FY 1990 Agency Initiatives and/or Augmentations (Observations)

(i) *Land Surface Data Systems.* The USGS plans to provide archiving, management, access, and distribution of land Earth science data sets for global change research applied to the study of solid Earth processes. (Addresses weaknesses i to iv; USGS: FY89=$0, FY90=$0.3M [This new $0.3M initiative will replace a $0.25M research program to yield a net budget augmentation of $0.05M].)

(ii) *Land Surface Processes.* The Earth Observing System (Eos) is specifically designed to observe the solid Earth and will be deployed in the late 1990s. (Addresses weaknesses i to iv; NASA: FY89=$0.9M, FY90=1.4M.)

Improving the Understanding of Solid Earth Processes

Strengths of Current Understanding

(i) *Volcanism.* The species of gases and types of aerosols associated with explosive and effusive volcanism are being investigated at many volcanos (see the section on Biogeochemical Dynamics). Submarine volcanic emanations and hydrothermal circulation are also being studied.

(ii) *Coastal Erosion and Inundation.* Geological processes associated with coastal erosion, deposition, and inundation, including areas undergoing subsidence or uplift, are under intensive study to determine future impact in coastal areas yet to be seriously affected by rising sea level.

(iii) *Permafrost.* The occurrence of permafrost and the conditions (past and present) under which it forms is relatively well known.

(iv) *Crustal Motion.* Deformation of the Earth's crust along plate boundaries is being intensively investigated with modern technology (e.g., EDM devices, VLBI, GPS, etc.). The magnitude, rate, and frequency of motion is important to determine. NOAA operates a number of World Data Centers, in cooperation with the International Union of Geology and Geophysics, which archive global data on solid Earth processes. NASA carries out long-term observations in support of solid Earth studies, including laser ranging and very-long baseline interferometry (VLBI) and GPS measurements, to determine crustal movements and sea level change. NASA also performs satellite gravity and magnetometer field measurements associated with solid Earth processes and provides support in data management of global change data for solid Earth studies, including the crustal dynamics data information system and the pilot land data system (PLDS).

Weaknesses in Current Understanding and High Priority Research Needs

(i) *Volcanism.* The volume of the various species of volcanic gases and aerosols entering the atmosphere and oceans on an annual basis is unknown. A much intensified research effort to better understand mid-ocean ridge volcanic processes is needed, including the unrestricted use of acoustic bathymetric imaging systems and sea-beam technology and increased use of submersibles (manned and unmanned) to make *in situ* observations and measurements and to collect samples. Long-term sampling of volcanic tephra, gases, and aerosols in the stratosphere is also needed to establish persistence (resident time) of such materials in the stratosphere and how particulate size and composition change with time following a major explosive volcanic event. (See the sections on Biogeochemical Dynamics and Climate and Hydrologic Systems.)

(ii) *Coastal Erosion and Inundation.* Additional studies of coastal areas most vulnerable to the rise in sea level are needed to better understand all the geological processes that influence the rate of inundation, the pedological processes associated with wetland loss, and coastal erosion. This is a high priority research need because of the potential environmental and economic impact of rising sea level on many of the heavily populated coastal regions.

(iii) *Glacier Fluctuation.* The neotectonic history of Antarctica may have exerted a powerful influence on ice sheet growth and decay; the extent and time scale of this process is totally unknown. Airborne and satellite remote sensing technology, existing or in development by NASA, can provide the tools to acquire the needed data. Major knowledge gaps involve a lack of understanding of the mechanism(s) involved when glaciers surge (rapid advance) and of the physics of fast-flow regimes (ice streams).

(iv) *Permafrost.* An increase in studies in permafrost regions is necessary to determine regional response to global warming and the contribution of newly released "greenhouse" gases to the atmosphere as permanently frozen ground melts. Gas hydrates in the ocean may also significantly contribute "greenhouse" gases to the ocean and atmosphere, yet little is known about their distribution, chemistry, and kinematics.

(v) *Crustal Motion.* Expanded research to improve our understanding of active tectonics is needed, as is unrestricted access to new technology, including the most accurate GPS data required for precise geodetic measurements of horizontal and vertical movements of land masses. Also needed are the most accurate GSN data for precise measurement of earthquakes and earthquake-related phenomena.

FY 1990 Agency Initiatives and/or Augmentations (Understanding)

(i) *Crustal Motion.* The NSF supports the Global Seismic Network (IRIS), the use of GPS (UNAVCO) for high-precision geodetic measurements of crustal motion, and a broad program of research on crustal dynamics. (Addresses weakness v; NSF: FY89=$4.5M, FY90=$4.8M.)

(ii) *Land Surface Data Systems.* The USGS plans to provide archiving, management, access, and distribution of land Earth science data sets for global change research applied to the study of solid Earth processes. (Addresses weaknesses i to iv; USGS: FY89=$0, FY90=$0.3M. [This new $0.3M initiative will replace a $0.25M research program to yield a net budget augmentation of $0.05M].)

(iii) *Land Surface Processes.* The Earth Observing System (Eos) is specifically designed to study a variety of solid Earth processes and will be deployed in the late 1990s. (Addresses weaknesses i to iii; NASA: FY89=$0.9M, FY90=$1.3M.)

Developing Predictive Models

Strengths of Current Models

(i) *Volcanism.* A long-term study of volcanic activity is being carried out by teams of interdisciplinary scientists at the Hawaiian Volcano Observatory and Cascades Volcano Observatory. Some predictive capability has been achieved in the cases of effusive volcanism in Hawaii and activity at Mount St. Helens. The science of volcanic eruption prediction is more mature than that of earthquake prediction.

(ii) *Permafrost/Ice.* Some progress has been made in developing models of expected temperature profiles in permafrost areas and in polar lake ice.

(iii) *Crustal Motion.* Long-term records of global seismicity have provided better initial understanding of the tectonics of plate boundaries, including associated volcanism.

Weaknesses in Current Models and High Priority Research Needs

(i) *Volcanism.* It is not yet possible to predict the magnitude of explosive volcanism or the precise timing of eruptions from infrequently active volcanos. Long-term observations of selected volcanos known to have historic record of explosive activity are required to provide the data needed to construct models of explosive volcanism. Models that can predict the atmospheric and oceanic impact of large explosive and effusive volcanic events (subaerial and submarine) also need to be refined.

(ii) *Coastal Erosion and Inundation.* Accurate topographic and pedologic models (maps) of coasts with barrier islands and other low-lying coastal areas must be developed to be able to predict the inundation and erosion of such areas in response to rising sea level.

(iii) *Permafrost.* Better models are needed to show the coupling of atmospheric warming to expected subsurface temperature profiles especially in polar areas.

(iv) *Crustal Motion.* The present state of seismological knowledge is insufficient to be able to develop models which can accurately forecast either the time or magnitude of earthquakes along plate boundaries.

FY 1990 Agency Initiatives and/or Augmentations (Models)

Coastal Erosions and Inundations. Topographic models of micro-relief in coastal regions are needed to predict the impact of rising sea level in such areas. NASA will acquire Eos data to measure topography. (Addresses weakness ii; NASA: FY89=$0.4, FY90=$0.6M.)

Solar Influences

The sun is now observed to be a variable star. Space and ground-based measurements have demonstrated solar luminosity variations of about 0.1 percent in association with solar activity. The most well-known, explainable climatic variations, the Ice Ages, were caused by small variations in the solar forcing of the terrestrial atmosphere. Thus the single most important solar problem in global change is the observation of solar variability and activity and the understanding of the effect of these on the chemistry and dynamics of the terrestrial atmosphere.

A good understanding of the mechanisms relating solar activity and climate is important in helping to properly evaluate the contribution due to "greenhouse" gases. In addition, such understanding will help in appreciating the type of climatic anomalies (like the 17th century Little Ice Age) that can be expected in the 21st century, whether or not "greenhouse" gases are controlled.

Of almost equal importance is the lack of knowledge on solar spectral irradiance variations. The properties of the atmosphere above 100 km are determined to a great extent by highly variable solar EUV radiations with wavelengths of less than 120 nm. An understanding of this layer is important because it controls satellite lifetimes; clearly, this has commercial, security, and scientific significance.

Some components of the energy incident on the upper atmosphere exhibit relative variations much larger than that of the total irradiance, as much as 10,000 percent over a solar cycle. These short wavelength photonic and energetic charged particle fluxes are associated with solar, and thus geomagnetic, activity, and principally affect regions of the atmosphere above 70 km in altitude. There they drive variations in temperature, density, dynamics, chemistry, ionization, etc. Radio communications are significantly affected by these energy input fluctuations. The amount of influence propagating from thermosphere to troposphere and the mechanisms of propagation–the teleconnections–are poorly understood.

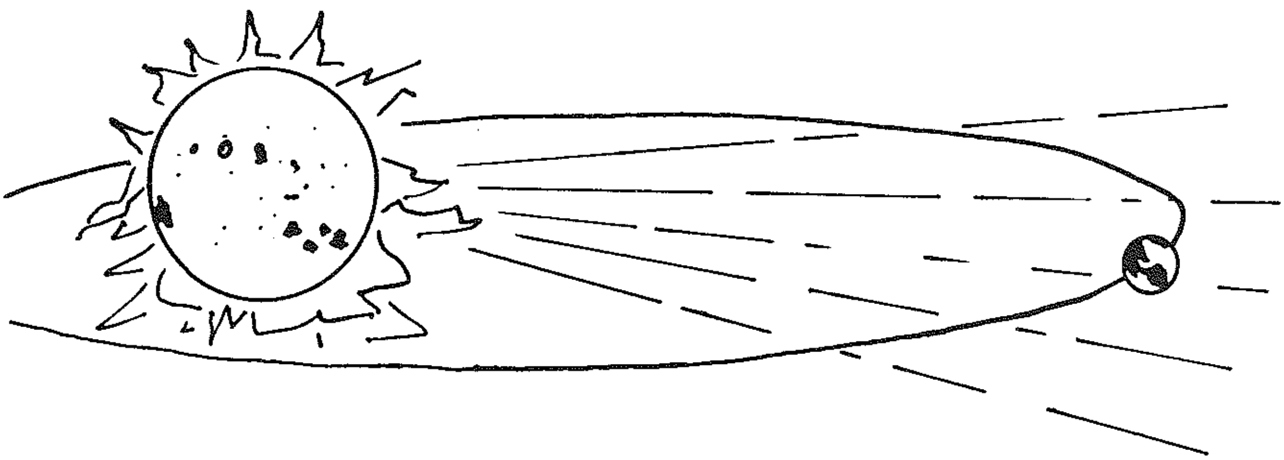


Figure 9. The Sun-Earth relations: Solar output, orbital characteristics, and the Earth as a receptor.

The most visible issue in the physics of the middle atmosphere (between 10 and 100 km) is the chemistry and dynamics of ozone. One of the major uncertainties in the study of global ozone trends and spatial distributions derives from lack of knowledge of the sun's UV variations at wavelengths greater than 120 nm and particularly between 180 and 320 nm. Ground-based proxies can be useful in the absence of spacecraft measurements.

Recently, strong statistical correlations between solar activity on the one hand and surface temperature and pressure on the other have been discovered. These correlations are observed in a data set which spans only three solar cycles. To predict what might be a major solar impact on climate requires capability, first to identify the mechanisms whereby solar variations influence climate, and then to predict the relevant solar variations. At present, appropriate data and necessary steps are lacking.

In summary, many avenues of research suggest distinct relationships between solar variability, solar magnetic activity, and the terrestrial atmosphere. Mechanisms are poorly understood, and the data on solar irradiance variations are sparse. The link from solar influences through the magnetosphere/upper atmosphere to the troposphere represents a severe gap in current knowledge.

Global-Scale, Long-Term Observations of Solar Influences

Strengths of Current Observational Programs

(i) *Solar Spectral Irradiance.* Intermittent solar spectral irradiance measurements have been made since the beginning of the Space Age. Future missions should provide continuous coverage of the solar spectrum. Relative precision of 1 percent in spectral emissions and 0.01 percent absolute accuracy in total emissions should be achievable according to recent laboratory studies. (NASA)

(ii) *Total Solar Irradiance.* Total solar irradiance measurements have been made from space with sufficient precision that the relationship between irradiance and the solar cycle is beginning to emerge. Programs are in place to ensure continual monitoring of other forms of solar energy input, e.g., from energetic particles and electrical currents. (NASA)

(iii) *Ground Based Solar Observations.* Ground-based programs can provide some proxy data in the absence of UV and EUV measurements. (NOAA, NSF)

(iv) *Sun-Climate Relationships.* Recent discoveries have reinforced a long-held contention that the sun contributes to climate/weather variability on time scales as short as months/years. (NSF)

(v) *Technological Advances.* New ground-based observation programs are beginning to use state-of-the-art charge-coupled devices (CCDs) and infrared arrays. It will soon be possible to obtain imaging solar photometry measurements with a relative precision of 1 part in 10,000 over a period of months. This will help resolve the issue of the origin of luminosity changes, i.e., are they due to surface temperature changes (now observed) or solar activity? (NOAA, NASA, NSF)

Weaknesses in Current Observational Programs and High Priority Research Needs

(i) *Calibration/Stability Difficulties.* Long-term stability of the onboard calibration of wavelength resolved satellite solar measurements needs to be improved. The UV wavelengths important to ozone production/ destruction are affected. The variability of the UV at wavelengths greater than about 200 nm over the solar cycle still lies within the calibration errors of existing spectrometers. These range from about 15 percent around 200 nm to perhaps 5 percent around 300 nm. The inability to predict the level of natural variability in the ozone layer and its distribution patterns worldwide can be traced in significant part to this uncertainty in the solar UV input. More solar UV measurements are needed from the NOAA satellite series in order to provide a long-term record of solar temporal variations that affect the stratosphere.

(ii) *Solar Variability and Ultraviolet Emissions.* Relevant UV and EUV wavelengths cannot be measured from the ground. Proxies are being developed that will perhaps help with reconstructing past global change, but modern measurements still suffer from this lack. The establishment of retrospective data banks would be greatly helped by proxy data, e.g., an index relating solar activity and UV emission. This area needs attention.

(iii) *Long-Term High Quality Irradiance Measurements.* The solar irradiance monitor (ACRIM) on board the Solar Maximum Mission (SMM) will be lost when SMM reenters the atmosphere in late 1989. Other spacecraft supply total irradiance measurements but ACRIM appears to have the best precision and stability. Comparable equipment will not be flown until the Upper Atmosphere Research Satellite (UARS) is launched in 1991; this disruption in continuity is unfortunate.

FY 1990 Agency Initiatives and/or Augmentations (Observations)

(i) *Ultraviolet Flux Measurements in Antarctica.* NSF will expand its UV flux measurement program in Antarctica to better understand the variability of solar UV in the southern polar region. (Addresses weakness ii; NSF: FY89=$1.5M, FY90=$2.5M.)

(ii) *Space Based Monitoring of Total Solar Irradiance.* NASA will continue its program of monitoring the total solar irradiance with ACRIM-type instruments to be flown aboard UARS, the Orbiting Solar Observatory, and Eos. (Addresses weakness iii; NASA: FY89=$0.7, FY90=$1.0.)

Improving the Understanding of Solar Influences

Strengths of Current Understanding

The sun drives all terrestrial systems, apart from the processes internal to the solid Earth. Fortunately, the sun is relatively constant, although recent observations have emphasized the sun's variability in all wavelength ranges. The basic problem is to understand the causes of solar variability and its impact on the terrestrial atmosphere. Although the variability is quite often small and the processes complex, some understanding has been established:

(i) *Sun-Climate Connection.* The major, most well-known climate variation, the "Ice Age," has a robust explanation that is due to changes in solar inputs as a consequence of small, slowly varying sun-Earth orbit changes. Thus, in the long-term, there is a firmly established sun-climate connection. (NSF)

(ii) *Variability in Solar Irradiance.* The solar irradiance variation is now established, and its connection to solar activity is understood in principle. Short term activity (days) reduces the irradiance, while the inverse is true over the longer term (years). Thus the "Maunder Minimum," a period of decreased activity in the 17th century, would be associated with lower irradiance and, therefore, reasonably connected to the "Little Ice Age" experienced in northern Europe. (NASA, NSF)

(iii) *Solar Cycle Influence on the Atmosphere.* Recent discoveries have been made connecting the solar activity cycle (11 years), the internal period of the atmosphere (2 years), and several atmospheric parameters (stratospheric temperatures, surface temperatures, etc.). This work has already been used to assist long range winter weather forecasts (NOAA, NWS) and to forecast polar stratospheric temperature. The latter is relevant to the antarctic ozone "hole." (NASA, NOAA, NSF)

(iv) *Drought-Solar Relationships.* Twenty-two-year (solar) and 18.6 year (lunar) signals are both observed in a number of Drought Area Index Series. Both have been implicated in separate kinds of climatic forcing of western U.S. droughts. (NOAA, NSF)

(v) *Solar Activity Influence on the Paleoclimate Record.* The carbon-14 (^{14}C) record, which is so important to all kinds of paleoclimate studies, is now beginning to be understood. The 11-year cyclic ^{14}C record is made "noisy" by solar-flare-produced ^{14}C excesses at solar maximum when cosmic-ray-induced ^{14}C is at a minimum. This work is important to understanding radionuclide production and its relation to climate trends (e.g., ^{10}Be, ^{14}C, etc., from ice cores). (NSF)

Weaknesses in Current Understanding and High Priority Research Needs

(i) *Time Scale Uncertainties.* A faint sun paradox notes that solar luminosity has increased by 25 percent over aeons while the atmosphere/ocean system has remained stable or declined in temperature. Conversely, over similar periods glacial advance was apparently triggered by small changes (0.1 percent) in solar inputs. Clearly, processes are operating on the longer time scales that are fundamental and yet are not understood. Their elucidation will assist the understanding on shorter time scales. It is possible that changes in atmospheric composition can compensate for these solar changes.

(ii) *The Nature of the Earth's Electrical Field.* Many processes in the atmosphere are electrical in nature, and yet scientists have only a rudimentary grasp of the global electric field and its response to internal (thunderstorm) and external (magnetosphere) forcing. Mechanisms relating the sun, cosmic rays, the global electric field, and tropospheric processes have been proposed, but suffer from a relative ignorance of middle atmosphere electrodynamics.

(iii) *Solar-Terrestrial Relationships.* Theoretical mechanisms relating solar inputs and terrestrial responses are virtually nonexistent.

(iv) *Energy Coupling to the Atmosphere.* The linkage of all forms of energy from the sun to the Earth involves processes not yet understood. In particular the connection between geospace/upper atmosphere/troposphere is not well understood. The NSF Coupled Energetics and Dynamics of Atmospheric Regions (CEDAR) program and the Geospace Environment Modeling (GEM) program are designed to overcome some of these deficiencies.

(v) *Solar Particle Influence on Atmospheric Composition.* There is now evidence that snow in Antarctica retains a chemical record (nitrates) induced by particle precipitation. This is due in part to ionization induced in the auroral zone and in part to solar particles. Clearly, the chemistry of nitrogen and oxygen must now include particle inputs, at least in polar regions.

FY 1990 Agency Initiatives and/or Augmentations (Understanding)

(i) *Coupled Energetics and Dynamics of Atmospheric Regions (CEDAR).* The NSF Global Geoscience Program will emphasize the study of the linkages of solar energy between geospace and the lower mesosphere by coordinated field campaigns using new and upgraded optical and radar equipment for remote sensing of the upper atmosphere. These studies will be carried out via the CEDAR initiative of NSF. (Addresses weakness iv; NSF: FY89=$0.7M, FY90=$1.9M.)

(ii) *Solar-Terrestrial Interactions.* DOE will support geosciences research on solar-terrestrial-atmospheric interactions and how this may force global changes in the environment. (Addresses weakness iii; DOE: FY89=$1.0M, FY90=$1.2M)

Developing Predictive Models

Strengths of Current Models

(i) *Theoretical Models of the Upper Atmosphere.* Rudimentary models of the ionosphere, thermosphere, and magnetosphere exist and can generate simulations of these systems from first principles. Thus, a basic understanding of coupling from the sun (solar wind) to the atmosphere (troposphere) can be attempted. (NASA, NOAA, NSF)

(ii) *Computational Equipment and Capabilities.* Advances in supercomputing capability, networking, and numerical techniques have permitted rapid improvement in the sophistication of the models. NSF, in particular, is making major investments in upgrading the National Supercomputer Centers and the interconnecting high speed networks. Faster supercomputers will be acquired, and backbone communication rates will advance from about 1.5 to 50 megabits/second. This will be invaluable in developing nonlinear 3-D models and facilitate handling of the massive data banks. This infrastructure will be important to such programs as CEDAR, GEM, and MAX91, where development and testing of coupled, global convection models is expected. (NSF)

(iii) *Upper Atmosphere Research Data base.* Testing of models with real data requires highly organized, centralized data centers covering all the appropriate parameters in a systematic fashion. Such a data set has been started at NCAR with the Radar Data base and is expanding to include all of CEDAR. This is facilitating much better model testing and integration of predictive Earth system models. (NSF)

(iv) *Solar Activity Research Capabilities.* Solar activity will most probably be very high at the next solar maximum (1991). NSF, NASA, and NOAA are collaborating in an observing program (MAX91) to take advantage of this situation. NASA will provide instruments for a Japanese satellite (SOLAR A). NSF will increase its ground-based observations. In particular, high-precision solar photometry will be undertaken to elucidate the solar variability/irradiance/magnetic activity/UV emission relationship. Part of the rationale for this work includes the development of proxies for radiations not seen at the ground. This will permit model testing (e.g., climate and photochemistry) on a long-term retrospective basis (i.e., decades to centuries). (NASA, NOAA, NSF)

Weaknesses in Current Models and High Priority Research Needs

In order to predict the sun-atmosphere connection, a truly interactive model covering the sun, solar wind, and the magnetosphere is needed. This is clearly a long way off, but short-term weaknesses and needs are outlined below.

(i) *Solar and Solar Wind Models.* Solar and solar wind models suitable for predicting the sun-atmosphere connection do not exist. The field has just not advanced far enough, and further development is needed.

(ii) *Model Integration.* The current models covering geospace/upper atmosphere/troposphere are not interactive. Basically, each model takes the output of one to be the input of the other. This is inadequate since the separate regions are known to be interactively coupled. The Air Force (AF) and NOAA jointly are trying to improve model integration (magnetosphere/ionosphere/thermosphere) for predictive purposes. AF and NASA have obvious operational needs that are not being met with current systems; hence, more effort is needed. This work is relevant to upper atmosphere modeling for satellite drag purposes and to spacecraft anomalies for commercial and security applications.

(iii) *Model Scaling Issues.* In common with many Earth system models, a problem exists in merging the different scale sizes. The models have to operate on a global scale, yet the internal processes are microscopic (e.g., raindrop formation within a global climate model). This problem of merging macro/micro properties infects all models. It requires better physics/chemistry, clever numerical techniques, and larger, faster computers.

(iv) *Three-Dimensional Models.* Many of the models are currently attempting only one- or two-dimensional simulations. Ultimately, for predictive purposes, fully three-dimensional, time dependent, nonlinear models are needed. The techniques are largely known, but the task is enormous, and more effort is needed in some cases.

FY 1990 Agency Initiatives and/or Augmentations (Models)

Fully predictive Sun-Earth modeling requires global standardized data sets covering as many years as necessary in order to confront three-dimensional, nonlinear models installed on massive supercomputers capable of handling the merging of the whole gamut of temporal and spatial scales from micro to macro. Clearly, this does not exist; however, the augmentation outlined below will make incremental progress toward this goal.

(i) *Global Modeling of the Upper Atmosphere.* The NSF Global Geoscience Program (CEDAR) will develop global models of the upper atmosphere/ionosphere. NCAR will develop an integrated, standardized data base. Approximately one third of the CEDAR effort will be aimed at this modeling objective. (Addresses weakness iii; NSF: FY89=$0.2M, FY90=$0.7M.)

Data Management

Success with the seven science elements will depend on the quality of data management available to support the global change scientific community. At the center of a long-term program for the study of global change must be the immediate development of a data management and information system for global change research. Management of all global-scale data sets is beyond the scope and resources of any single agency or country. It includes means and mechanisms to describe, gather, transmit, validate, process, analyze, archive, model, and disseminate the interdisciplinary data needed to understand the scientific interactions of Earth processes on a global scale.

An infrastructure for data management and information systems must be shared and used by scientists and agencies performing research in all seven of the U.S. Global Change Research Program science elements. The initial focus of such a system will, of necessity, be on (1) management of global-scale, long-term data from observation systems, (2) organization of data sets to improve understanding of global change processes, and (3) analyses and preparation of data sets for the development and validation of predictive global change models.

Management of Global-Scale, Long-Term Data from Observation Systems. The dominant problem facing scientists attempting to use global change data sets is that it is extremely difficult to find who has what data and how good the data are. Once a research problem is decided on, traditional research begins with a review of the relevant literature to ascertain the thinking and experiments of others on the topic. An analogous process for data (i.e., for scientists in the different science elements to begin by also reviewing the data and information resources used by others on the topic) is virtually impossible today. Once the architecture for an infrastructure for a data management and information system is agreed upon, the essential precondition will be in place to improve understanding of global change processes and to develop successful predictive models.

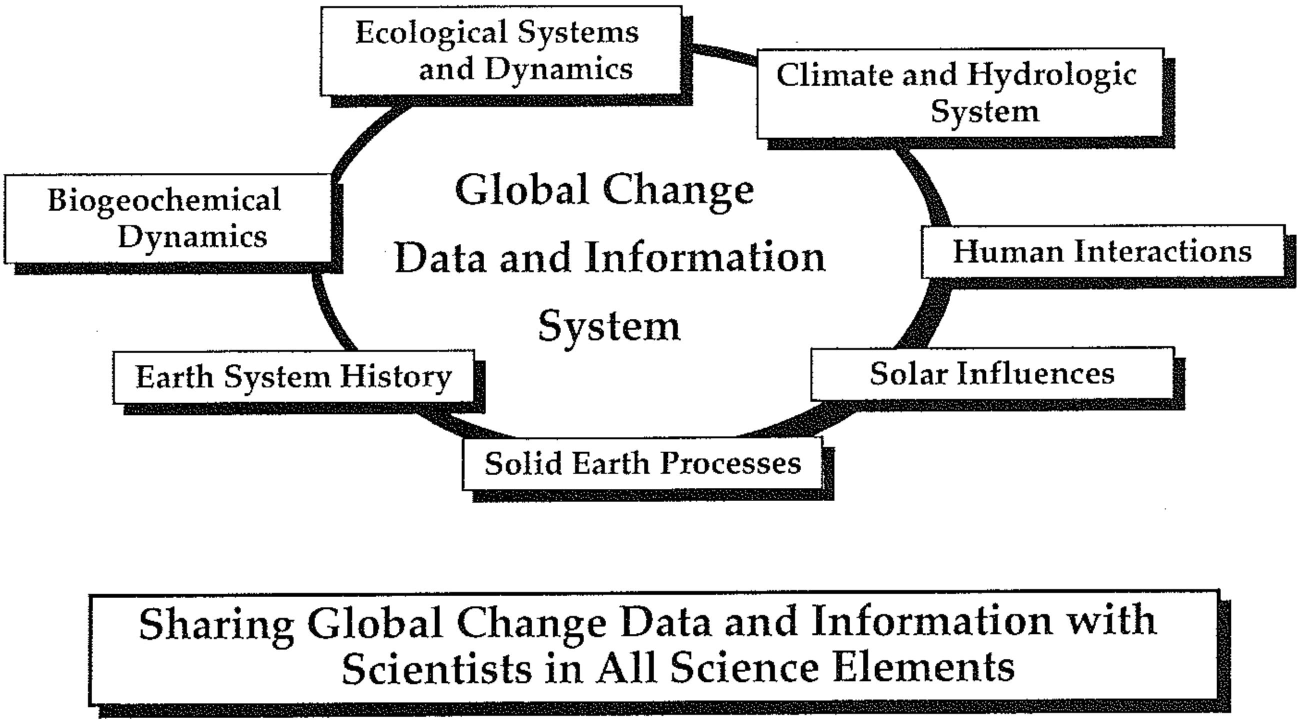


Figure 10. Data management for the U.S. Global Change Research Program.

Organization of Data Sets to Improve Understanding of Global Change Processes. Data sets at global, regional, local, and micro scales will need to be assembled to understand global change processes. Many of these will be built from the analysis and interpretation of existing and future satellite data streams. Others will be pieced together from diverse sets of *in situ* observations and measurements, initially using retrospective data, but augmented and completed with data collected in the future specifically for this purpose. Earth scientists must work with data managers and computer scientists to identify, construct, and disseminate these global-scale data sets that will best improve the understanding of global change processes.

Analyses and Preparation of Data Sets for the Development and Validation of Predictive Global Change Models. Three elements must interact for predictive modeling to succeed. Modelers must be able to identify the data sets they need for their models at global, regional, local, and micro scales. Observation systems must be able to collect the data needed by modelers. A shared data management and information system must be able to act as intermediary to help reduce the data, then catalog, store, and distribute the data and information products from both the observing systems and the process modelers. There is an obvious need for users of data sets to inform the providers of what they need, of the providers of data sets to inform the users about the attributes and quality of the data, and of the data-management and information system to facilitate both. In short, the data management and information system requires an end-to-end process with users and providers interacting with each other by means of the shared system.

- *Raw data and derived products.* Because of the interdisciplinary, long-term nature of global change studies, most requests to the data management system are likely not to be for the raw observational data themselves, but rather for derived products such as global analyses or edited data collections in association with descriptive text or graphic material. Thus, the system must be oriented to provide information rather than just data and must play a perceptive role in the generation, acquisition, quality control, and dissemination of such value-added products. Scientists will require information in different forms and from different information sources, depending on the context. Information form includes imagery, numeric data, and text, and scientists will want to take advantage of increasingly modern technologies such as hypermedia to integrate the diverse data sets.

- *Documentation of data.* To be useful for global change studies, data and derived information will normally need to have uncertainties less than what scientists determine to be "significant." Sustained global measurements must result, on a routine basis, in analyzed fields of well-defined accuracy, including the effects of instrument calibrations, coverage in space and time, sampling, quality control and data editing, the algorithms used for data reduction, the adequacy of ancillary data needed in those algorithms, the validation of those algorithms, the assimilation or analysis procedures used, the availability of independent measurements for spot checking the conclusions, and the documentation of all of the above. Without consistent documentation, data sets have very limited value to those not familiar with their origins and can easily be misapplied.

- *20-year test for data.* To be useful for global change studies, data sets must pass the 20-year test: Can our successors 20 years from now tell with confidence that the changes they observe are real rather than artifacts of some aspect of the measurement or analysis process? The key is to collect data of sufficient precision and accuracy to support the investigations. These requirements pose an enormous challenge to the way we approach research and research support. For example, sea-surface temperature might be used as a measure of global temperature. To assume that a 1-degree centigrade change in sea-surface temperature over 20 years is significant requires that the global sea-surface temperature data set must be validated consistently for the period of record well within 1 degree (e.g., a few tenths of a degree). Not only must the measurements be well within one degree, but the effects of different measurement techniques, instrument calibrations, and analysis procedures must all have been well within one degree. The 20-year test also requires that the data set cannot have unresolvable gaps in space or in time. Such a sea-surface temperature data set does not exist today.

- *Few well-documented global data sets exist.* While the maximum tolerable uncertainty will be different from variable to variable, and most have yet to be defined, only a very few documented data sets exist today that fall within expected requirements. A case can be made only for solar irradiance, carbon dioxide, surface-atmosphere pressure, and land-surface characteristics.

- *Common infrastructure on data management is essential.* In the absence of a common infrastructure on data management and information systems, the immense diversity and quantity of both raw and derived data generated by the sensor platforms and researchers' computer workstations will overwhelm attempts to find, much less use and synthesize, relevant data. A shared underlying framework of technological support, consistent across agencies and that involves and supports the university and other user communities, provides a viable and economical means to improve the returns on the nation's investment in global change data collection and analysis. Existing facilities and skills can be used to the greatest possible extent by linking with a common architecture such that directories, catalogs, and inventories of data may be constructed and used by researchers in all global change science elements. Each discipline or institution continuing to go its own way, building incompatible and inaccessible data "systems," would stifle progress towards a useful national data system for global change research.

- Da*ta management is complex, but vital to all global change science elements.* To be useful, a process must be put in place that will make it as easy as possible for scientists to use global change data. Such a process, common to all of the global change science elements, is vital to support studies within a science element and other studies that require data to be shared by two or more of the science elements. The data management system must be able to accept and store dissimilar types of data, collected from very different data collection systems, by different organizations, in different formats, on different media. Then, the system must be able to deliver the data economically to interested scientists in the United States and elsewhere and assist in integrating and analyzing these data in a manner consistent with the data's documented accuracy.

- *Synoptic data are needed.* There is a need for spatially-analyzed 3-D vector fields of the state variables of the system to describe the global system at any given point in time. These are usually constructed with 2-D horizontal fields at discrete vertical intervals (height or depth). These often are termed synoptic data.

- *Time-series data are needed.* Time series (as long as possible) data of the state variables are required to capture and understand the fluctuations of the global system. Time-series data usually comprise either successive snapshots of synoptic fields at discrete time intervals or an ensemble of scalar measurements of a parameter or index at a point in space representing a limited 2- or 3-D zone around it.

- *Rate of change depends on parameter in question.* Long-term time averages of either synoptic fields or time series of the state variables provide the relative mean state or the "reference state" of the system. Departures from the relative mean state are often used to monitor fluctuations of the global system and derive measures of the variability of the system. Changes in the relative mean state and variability are commonly defined as "change." If the time series were infinitely long, the relative mean state would be the absolute mean state and thereby constant. Due to the complexity of the global system, a vast variety of space and time scales are involved. The time frequency at which a state variable or parameter needs to be sampled depends on the rate of change of the parameter in question and the relative errors of measurement and could range from seconds (micro-physical processes) to days (atmosphere and weather) to seasons and years and decades (vegetation, ocean circulation), to centuries and thousands of years.

- *Global, regional, local, micro, and proxy data are needed.* The data sets required would range in space scale from global to regional to *in situ* (local to micro), depending on use or application. For example, monitoring, diagnostics, and predictive general-circulation models generally require global data sets. These data are also needed for verification and validation of global-system simulation models. Understanding and parameterizing small-scale processes require high-resolution data sets over limited space and time boundaries. Due to the lack of instrumental records covering sufficiently long time periods, specialized analyses are required of proxy records (tree rings, ice cores) to construct a picture of the prehistorical global system and its fluctuations.

- *Data management requires institutional and international cooperation.* For most global change studies, global data and information will be required. No one nation, agency, or institution will be able to gather the appropriate data without cooperation from other nations, other agencies, and other institutions. Individual agencies will need the cooperation of others to collect, manage, and preserve data sets systematically for global change and make them accessible across the traditional discipline and agency boundaries.

- *Interagency response to the data management problem.* The importance and complexity of the data management challenge have already been recognized within the Federal agencies. In 1987, they formed the ad hoc Interagency Working Group on Data Management for Global Change (IWGDMGC). Participating agencies (NASA, NOAA, NSF, USGS, and the Departments of Energy, Agriculture, Navy, and State) are being advised by the National Academy of Sciences' Committee on Geophysical Data. Building on a core of existing national data centers together with the university and international data groups, the IWGDMGC is coordinating plans to establish a program for the management of data and information that will support global change research.

- *Data management issues affect all science elements and all objectives.* The initial thrust of the data management program will need to be focused on monitoring and observation systems (due to the close links between data gathering and data management). But, data management issues also impact the ability of the research program to improve understanding of global change processes and are integral to successful predictive modeling. Strengths and weaknesses related to data management are not all identified below, although key topics that span several science elements are concentrated in this section for emphasis.

Many data management issues are embedded in sections of this report covering the seven interdisciplinary science elements. For example, references to several activities, and to programs such as Eos (Earth Observing System), ISLSCP (International Satellite Land Surface Climatology Project), TOGA (Tropical Oceans Global Atmosphere), and WOCE (World Ocean Circulation Experiment) with important data management aspects pervade the science elements. (For this reason, the dollar totals identified below for data management will not balance with budget estimates for data management in *Our Changing Planet: A U.S. Strategy for Global Change Research.)*

Management of Global-Scale, Long-Term Data from Observation Systems

Strengths of Current Management of Global-Scale, Long-Term Data from Observation Systems

(i) *Available Technology.* Technologies (sensors, computers, telecommunications, data storage media, electronic publication) exist that are capable of capturing, processing, preserving, distributing, and making accessible global-scale data sets.

(ii) *Data Center Structure.* The data centers that are most effective in management and use of global-scale data sets are those where scientists actively participate with data managers.

(iii) *Interagency Framework for Data Directory.* Coordinated interagency activity is under way to construct a data directory that describes global change data holdings (including long-term global-scale data sets) of all participating agencies and academic institutions.

(iv) *Some Data Sets.* Well documented, long-term data are available for some, although few, variables (e.g., carbon dioxide, solar irradiance, surface atmosphere pressure, and land-surface characteristics).

(v) *Arctic Environmental Data System.* Experiments are being conducted, sponsored by the Interagency Arctic Research Policy Committee (IARPC) in cooperation with the IWGDMGC, to use arctic data sets and arctic mesoscale studies related to global change as a testbed for data management concepts that might be useful in global change studies. The testbed approach for the Arctic Environmental Data System (AEDS) not only helps arctic scientists immediately, but also provides a creative environment for experimenting quickly with storage media, information distribution techniques, links between scientific data and bibliographic information, and data directories.

Weaknesses in Current Management of Global-Scale, Long-Term Data from Observation Systems and High Priority Research Needs

(i) *Data Quality.* Many data sets from present data systems lack credibility due to inconsistent documentation (e.g., incomplete description of instrument calibrations, algorithms used for data reduction, coverage in time and space, quality control, and data editing).

(ii) *Nonuniform Data Management Procedures.* The absence of established criteria or policies for evaluating suitability of data sets for global change studies, for archiving and retaining data sets in data centers or by project teams, and for purging data sets has impeded the construction, management, and use of long-term, global-scale data sets from observing systems.

(iii) *Nonuniform Technologies.* While new technology is providing much-needed tools for managing our Nation's data, this technology is noticeably lacking in our Federal data centers. Technologies are not applied in a coordinated manner to the management of and access to global-scale data sets.

(iv) *Inadequate Infrastructure.* While quantities of observational data will increase dramatically, primarily from new satellite systems such as the Earth Observing System (Eos) but also from the assembly of global-scale retrospective data sets, the data systems technologies and support infrastructure are not yet in place to support scientific data analysis.

(v) *Operational Data Sets.* Many large data sets that might seem suitable for global change process studies have been collected from operational systems (e.g., ocean navigation) and are not presently suitable to support scientific studies.

(vi) *Limited Global Data on Global Change.* At present very few global data sets have been compiled and processed for the specific purpose of monitoring and detecting climate change. Most scientific hypotheses are based on inadequate data sets. A substantial effort to collect and process historical observations into global data sets will be required.

(vii) *Calibration of Satellite Data.* Despite 25 years of satellite observations, only a single satellite-based data set is sufficiently well calibrated to document global change (from TOMS, the Total Ozone Mapping Spectrometer). A substantial back-processing effort will be required to construct such data sets and to provide time continuity when they are used with future Eos observations.

(viii) *Inadequate Resources for Data Management.* Many data centers suffer from diminishing resources and attention, even while demand for data by scientists increases. Quality control suffers as reduced funds are applied to the operational needs of archiving and distribution.

(ix) *Data Management Structures.* Comprehensive data centers and data-exchange standards, are completely lacking for certain disciplines, including biology and ecology.

(x) *Coordination.* While some agency initiatives or augmentations for studies of global change do contain resources for data management, they are too diffuse and lack coordination. At present, separate agency budget submissions force funding for data management to reduce resources available for science.

(xi) *Global Information System Test Capability.* Lack of global information system test capability impedes progress in identifying major data-management problems, such as systematic barriers between data collection and data needs of process studies.

(xii) *Data Management for Global Change Research.* The data management and information system for meteorological observations is relatively advanced, but inadequate for global change research. Most data are poorly documented and are of uncertain quality, and some important data are not accessible. This inaccessibility has limited the development of long climate records of the ocean and atmosphere. For example, historical marine data during the two world wars exist but are not included in any analyses, because they are not digitized.

FY 1990 Agency Initiatives and/or Augmentations (Data Management)

(i) *Land Surface Data Systems.* Provide for permanent archive, management, access and distribution of land Earth-science data sets for global change research. Includes transfer of remotely sensed data (e.g., Landsat) to nonvolatile storage media, archive of selected USGS data sets for global change, and access to land data maintained by Federal agencies. (Addresses weaknesses i to iv and vii; USGS: FY89=$0, FY90=$3.0M.)

(ii) *NOAA Climate and Global Change Data Management Services.* Improve long-term data management support for NOAA program elements, including data bases on trace gases, global hydrologic cycle, and enhanced data support for predictive climate change models on time scales of seasons to decades and centuries. Strengthening of observational networks also requires support for activities that lead to climate data bases, data sets, and data fields that meet user requirements and can be easily accessed by the global change community. (Addresses weaknesses iii to viii and xii; NOAA: FY89=$0.8M, FY90=$2.5M.)

(iii) *Interagency Working Group on Data Management for Global Change.* Establish and coordinate a Global Change Data and Information System by 1995 that is consistent across agencies and involves and supports the university and other user communities, with the purpose of making it as easy as possible for scientists to access and use global change data. (Addresses weaknesses i, iv to ix, and xi; DOE: FY89=$0.1M, FY90=$0.2M; NASA: FY89=$0.1M, FY90=$0.2M; NOAA: FY89=$0.2M, FY90=$0.5M; NSF: FY89=$0.1M, FY90=$0.2M; USGS: FY89=$0.1M, FY90=$0.2M; U.S. Navy (USN): FY89=$0.1M, FY90=$0.2M.)

Organization of Data Sets to Improve the Understanding of Global Change Processes

Strengths of Current Organization of Data Sets to Improve Understanding

(i) *Research Data Sets.* Project data sets resulting from scientific process studies of limited duration that involve experimental observations are often invaluable for further individual research (e.g., in solid Earth process studies).

(ii) *Research Data Facilities.* A few scientific disciplines (e.g., meteorology, hydrology) are able to improve understanding due to support by successful data facilities (such as the National Center for Atmospheric Research [NCAR], the Unidata Project at the University Corporation for Atmospheric Research, and the USGS Water Data Storage and Retrieval System [WATSTORE]) where data management, science, and adequate technology converge.

(iii) *Prototype Data Facility.* A prototype, problem-oriented data facility has been created, with notable success, to promote the integration of information related to carbon dioxide from many disciplines (Department of Energy's Carbon Dioxide Information Analysis Center). This model might be used by other data centers to foster greater integration of information across traditional discipline boundaries.

Weaknesses in Current Organization of Data Sets and High Priority Research Needs to Improve Understanding of Global Change Processes

(i) *Documentation and Archiving*. Project data sets are often collected in analog form, which precludes widespread distribution and subsequent use of these data. Projects usually do not request funds for documentation and archiving of project data.

(ii) *Limited Access to Existing Data*. Understanding global change processes requires the exploitation of existing data to the maximum possible extent. However, retrospective data sets are poorly catalogued, inconsistently documented, inaccessible, and have no disciplined publication process .

(iii) *Coordination of Data Processing*. Many data sets thought to be vital to the understanding of global change processes are not in computerized form (e.g., paleoclimate data). Potential users would typically have access to computers to use such data, but no coordinated program exists to computerize the data and make it available.

(iv) *Artifact Free Data*. To pass the 20-year test ("Can scientists 20 years hence have confidence that global changes observed are real rather than artifacts of the measurement or analysis process?"), new approaches to data management and data centers must emerge to include partnership between scientists and data managers, and a new focus must be developed on documentation to describe and support the raw data.

(v) *Data Integration*. National data centers have inadequate linkages that do not foster access to or integration of data from different science elements. For example, ecological studies and climate studies suffer from absence of coordination between their respective data centers.

(vi) *Data Formats*. Data formats and exchange mechanisms are inadequately standardized. Standards that do exist are not uniformly adhered to by the scientific community. This thwarts even the most persistent scientists and data generators who attempt to combine or present data from the different science elements.

(vii) *Data Collection*. Several, if not all, existing global data sets contain data collected for operational purposes, such as for the routing of ships and aircraft. These data have time and space resolution substantially less than the observing station networks that would be necessary to study global change processes. Very few have been augmented by new collection efforts. A special program is required to fill the gaps in these data sets by collecting and processing an approximately tenfold increase in the number of stations for basic observations (e.g., temperature, precipitation) for the past 50 to 100 years.

(viii) *Interdisciplinary Data Management*. National Data Centers have traditionally been discipline-oriented, while global change research is problem-oriented. Problem-oriented data centers are needed to promote the integration of information across discipline boundaries.

Analyses and Preparation of Data Sets for the Development and Validation of Predictive Global Change Models

Strengths of Current Analyses and Preparation of Data Sets

(i) *Assimilation Models.* Assimilation models produce enormous data sets describing variables with known and/or uniform characteristics. These well-documented, derived data fill gaps in space or time; ensure physical, chemical, or biological consistency; and can be used by multiple applications until superior data are available.

Weaknesses in Current Analyses and Preparation of Data Sets and High Priority Research Needs

(i) *Data for Modeling Purposes.* Global data sets (e.g., soil moisture) are not developed to support modeling efforts. Of 70 data sets identified in the NASA Advisory Council's *Earth System Science: A Closer View,* most cannot be used in scientific analyses or modeling efforts. Automated methods to integrate global-scale satellite and *in situ* data sets must be developed and applied.

(ii) *Global-Scale Observational Data.* Data needs of global models have not traditionally driven the data-collection or data management process. Rather, modelers have had to make do with adapting data sets organized along needs of disciplinary studies. The usefulness of global change models will be limited until data collection and processing responds to the needs of mathematical models by providing sustained, well-calibrated, global-scale data sets of observations.

(iii) *Proxy Records.* Past records, both instrumental and proxy, must be analyzed to improve the basis for testing models. The lack of coordinated data management activities among national data centers and project scientists reduces the capabilities to capitalize on applying retrospective data to models.

(iv) *Model Validation.* Lack of well-defined and validated modeling requirements for data complicates the design of data collection activities.

PRIORITY FRAMEWORK FOR THE U.S. GLOBAL CHANGE RESEARCH PROGRAM

The Committee on Earth Sciences (CES) has developed a multi-level, priority-setting framework that can be used to focus and integrate program development and budget proposals. In order to address the U.S. Global Change Research Program goal of establishing the scientific basis for sound policy formulation, CES has identified several high priority research activities for each of the seven science elements (See Figure 11). These represent our current understanding of the most serious intellectual hurdles limiting: (i) knowledge of the controlling processes of global change, and (ii) our capacity to develop comprehensive predictive capabilities. The initial phases for implementing the U.S. Global Change Research Program will be taken in the context of these research priorities. However, long-term planning will be undertaken over the next several years in close collaboration with the NAS Committee on Global Change and appropriate international and intergovernmental bodies and integrated into future revisions of this plan. Thus, it is likely and expected that the priority framework will evolve over time.

The following sections briefly outline the highest priority initial research themes for each of the seven science elements. The exact nature of specific program proposals and scientific plans to address each of these themes will be developed by the Federal agencies in close collaboration with the broad scientific community, both domestically and internationally.

These initial priorities are derived from numerous recommendations and research priorities outlined by the science community (ESSC Report, NAS/CGC Initial Priorities for the IGBP, etc.). The initial priority framework outlined herein is structured around those recommendations and from the goals and objectives stated in the U.S. Global Change Research Program strategy document entitled *Our Changing Planet: A U.S. Strategy for Global Change Research.* The framework uses a multi-level priority structure:

- *Strategic Priorities.* A set of overarching priorities that apply to all programs, projects, or activities within the U.S. Global Change Research Program.
- *Integrating Priorities.* The set of three U.S. Global Change Research Program objectives designed to integrate the total program. Any research effort within the program must contribute to one or more of these objectives.
- *Science Priorities.* A set of implementation-level activities that are the "first order" science priorities of the U.S. Global Change Research Program. These are the highest priority elements of the Program.

Strategic Priorities

The major purposes for establishing strategic priorities are to provide an overall framework to help determine the key elements of the U.S. Global Change Research Program, to keep the focus on the most central goals and objectives of the Program, and to compare budget decisions against broad strategic guidelines. The following research program characteristics are deemed to be of high strategic importance:

- *Supports Broad U.S. and International Scientific Effort.* Supports a broad U.S. and international effort to improve the scientific basis needed to address the environmental, societal, and economic challenges related to global change.

- *Identifies Natural and Human-Induced Changes.* Distinguishes natural changes from industrial, social, and other forms of human-induced changes.

- *Focuses on Interactions and Interdisciplinary Science.* Advances the scientific understanding of global change processes through a fundamental research program that focuses on the interactions among the physical, geological, chemical, biological, and social processes.

- *Shares Financial Burden, Uses Best Resources, and Encourages Full Participation.* Shares the financial burden nationally and internationally, utilizes the best physical and intellectual resources, and encourages the full participation of all nations.

Integrating Priorities

The U.S. Global Change Research Program has three parallel and interrelated scientific objectives, one or more of which must be served by any research program, project, or activity of the Program. These scientific objectives also serve as the following integrating priorities:

- Establish an integrated, comprehensive long-term program of documenting the Earth system on a global scale through:

  - Observational programs
  - Data management systems

- Conduct a program of focused studies to improve our understanding of the physical, geological, chemical, biological and social processes that influence Earth system processes and trends on global and regional scales.

- Develop integrated conceptual and predictive Earth system models.

Science Priorities

The science priorities are drawn from (i) the CES Analysis of the Strengths and Weaknesses of the Current U.S. Global Change Research Program and FY 1990 Initiatives (see previous chapter), (ii) the 1988 NAS report entitled *Toward an Understanding of Global Change*, (iii) the 1984 WMO and ICSU report entitled *Scientific Plan for the World Climate Research Programme*, (iv) the 1988 Earth System Sciences Committee Report entitled *Earth System Science: A Closer View*, and (v) the 1988 ICSU report entitled *The International Geosphere-Biosphere Programme: A Study of Global Change – A Plan for Action.*

The science priorities are shown schematically in Figure 11. The science elements are ordered from left to right in decreasing order of priority (Figure 11). Within each of the seven science elements, the research activities are listed in descending order of priority. These priorities are designed to ensure that the U.S. Global Change Research Program effort maintains a robust research base that can make the optimum progress toward resolving the most significant uncertainties with a given level of support.

Although the priorities are ordered along each axis of the matrix, the importance of neighboring elements is similar and virtually interchangeable. Additionally, because of the evaluation criteria listed below (i.e., relevance, merit, readiness, cost, etc.), the prioritization of activities in each science element does not preclude the funding of lower priority activities. There is a clear recognition that a successful U.S. Global Change Research Program must include efforts in each of the seven science elements and, in many instances, the research activities shown in the matrix are complementary, hence funding one scientific activity may influence the priority of others. For any given funding level, the mix of activities both within and between science elements will be determined through an iterative process involving many participants – the CES, the National Academy of Sciences, and others.

The following is a specific and more detailed description of the science priorities for each of the seven science elements. Again, it is likely and expected that these priorities will change as scientific understanding and capabilities evolve.

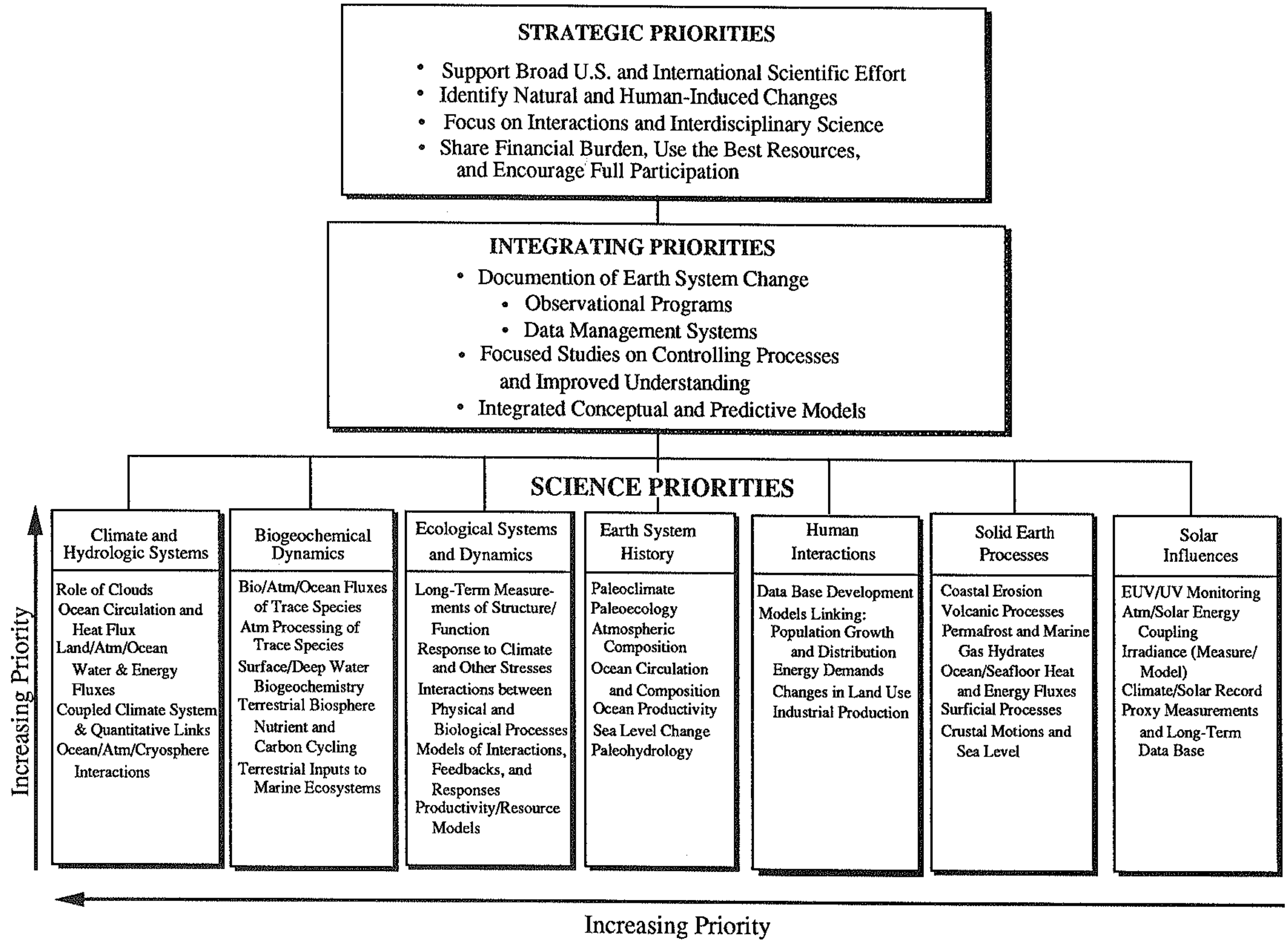


Figure 11. U.S. Global Change Research Program Priority Framework

Climate and Hydrologic Systems

Role of Clouds. This element addresses (i) critically needed improvements in our understanding of cloud-radiation feedback mechanisms as they influence climate change on all time scales, and (ii) proper representation of cloud mechanisms in coupled general circulation models. Work on cloud climatologies (monitoring) and cloud feedback mechanisms (processes research) and parameterization (in models) are all priorities within this category.

Climate and Hydrological Systems
Role of Clouds Ocean Circulation and Heat Flux Land/Atm/Ocean Water & Energy Fluxes Coupled Climate System & Quantitative Links Ocean/Atm/Cryosphere Interactions

Ocean Circulation and Heat Flux. This activity will address a critical lack in our dynamical description of the ocean-atmosphere system and its potential for interaction with biogeochemical processes. A global-scale, four-dimensional description of oceanic circulation, density fields, and temperature distribution is needed to close the gap between our understanding of oceanic versus atmospheric processes on climate time scales. Oceanic processes represent a substantial "short circuit" for poleward heat flux in response to radiative forcing in the Earth's tropical regions. The magnitude and time variability of these processes is a critical dimension of global change research.

Water and Energy Fluxes. Fluxes of water and associated state changes throughout the atmosphere represent a dominant force in the workings of the integrated Earth system. The global distribution of water vapor (the primary "greenhouse" gas), its source in convective exchange with the ocean, and its loss to the atmosphere through varying patterns of precipitation are a primary key to understanding how the Earth system works and how it responds to changes in radiative forcing. Changing fields of convection and precipitation over oceanic regions will be a major observational and modeling focus. Another key element of the global hydrological cycle is understanding the effects of terrestrial vegetation on land surface characteristics that influence the exchange of water between system components. Variable precipitation patterns over land as they are manifested in land surface hydrology also will be addressed.

Behavior of Coupled Climate System, Feedbacks, and Quantitative Links. This element supports research into the behavioral characteristics of coupled systems of atmosphere, ocean, cryosphere, land surface, and biosphere. The identification of underlying order in such a nonlinear system cannot be achieved solely by studying individual components, such as clouds, ocean circulation, or hydrological cycle. How these components act together to affect natural variability on all time scales will be the subject of considerable focus in the research program. Studies of the potential for relatively sudden transitions within the natural system and model experimentation of transient responses of the system to external forcing lie within this category.

Ocean, Atmosphere, and Cryosphere Interactions. This element will address two Earth system problems: (i) the interactive processes between the atmosphere, ocean, and sea ice, that affect relatively short-term changes in climate, and (ii) the amount and variability of fresh water stored in the polar ice sheets as they affect the long-term evolution in the Earth system.

Biogeochemical Dynamics

Fluxes of Radiatively and Chemically Active Species Between the Atmosphere, Biosphere, and Land and Ocean Surfaces. Initial emphasis will be on understanding the natural and anthropogenic processes that regulate the fluxes of: (1) radiatively active long-lived gases released to the atmosphere, e.g., methane; (2) chemically active short-lived atmosphere species that influence oxidant and acid formation and the microphysical nature of clouds and aerosols; and (3) carbon and nutrient species exchange between the air, sea, land, and biota.

Biogeochemical Dynamics
Bio/Atm/Ocean Fluxes of Trace Species Atm Processing of Trace Species Surface/Deep Water Biogeochemistry Terrestrial Biosphere Nutrient and Carbon Cycling Terrestrial Inputs to Marine Ecosystems

Atmospheric Cycling and Transformations of Radiatively and Chemically Important Trace Species. Initial emphasis will be on understanding: (1) the chemical and physical processes that control the atmospheric (stratospheric and tropospheric) distributions and lifetimes of climatically, chemically and biologically important trace species; and (2) how changes might be induced in the atmospheric chemical processing and removal mechanisms for these species.

Biogeochemical Processes Responsible for the Exchange of Carbon and Nutrients Between the Surface, Deep Ocean Waters, and Sediments. Initial priority will be on identifying and quantifying the processes operative in ocean basins and coastal oceans that control the flux of carbon and other biologically and climatically important elements to the deep ocean waters and exchanges between the oceans and modern marine sediments.

Cycling and Transformation Within the Terrestrial Biosphere of Nutrients and Carbon. Initial priorities will be on understanding the role of the terrestrial biosphere in (1) regulating the global carbon cycle, and (2) utilization and exchange of nutrient elements with surrounding environmental media.

Terrestrial Flux of Nutrients and Carbon to Coastal Waters and Oceanic Ecosystem. Initial priority will be focused on studying the role that major terrestrial landscapes play in supplying nutrients and carbon to coastal ocean regions and how changes in land use practices can perturb these inputs.

Ecological Systems and Dynamics

Long-Term Measurements of Structure/Function. Systematic sampling and monitoring are essential to document critical natural versus human-induced changes (e.g., "forest die-back" versus natural succession of vegetation) in the structure and function of globally relevant biological systems on various time scales.

Response to Carbon Dioxide, Climate, and Physical/Chemical Stresses. Laboratory and field studies are needed to improve the understanding of how species, ecological communities, managed ecosystems, and natural ecosystems (terrestrial, aquatic, and marine) respond to climate and other stresses. Research is especially needed on responses to multiple stresses (e.g., simultaneous elevated carbon dioxide and moisture stress).

Ecological Systems and Dynamics
Long-Term Measurements of Structure/ Function Response to Climate and Other Stresses Interactions between Physical and Biological Processes Models of Interactions, Feedbacks, and Responses Productivity/Resource Models

Interactions between Physical and Biological Processes. Initial priority must be on improving measurements and the theoretical basis for interactions between physical and biological processes on varying time and space scales, and how the large-scale interactions influence processes at the smaller scales (e.g., the interaction of climatic variables on phytoplankton dynamics or the reproduction of forest trees).

Models of Interactions, Feedbacks, and Responses. Models will be developed at appropriate scales to develop a theoretical basis for linking ecology to physical climate dynamics in order to predict ecosystem response and feedbacks on climate and atmospheric composition.

Productivity/Resource Models. Models will be developed to predict and assess biological productivity and natural resource dynamics, especially agriculture, marine and forest resources.

Earth System History

Paleoclimate. Research will be carried out to reconstruct past climates on regional and global scales. Objectives will include (1) documenting the natural variability of climate on all time scales (decades or less to millions of years), (2) reconstructing the consequences of past climate changes, (3) determining past rates of climate change, (4) improving understanding of causes of climate change, and (5) validation of climate models.

Earth System History
Paleoclimate Paleoecology Atmospheric Composition Ocean Circulation and Composition Ocean Productivity Sea Level Change Paleohydrology

Paleoecology. Research to reconstruct past ecological conditions and how ecosystems have responded in the past to climate change will be conducted.

Atmospheric Composition. Research will be conducted to document the history of changes in the earlier composition of the Earth's atmosphere through time, e.g., studies of gas composition of air bubbles trapped in glacier ice.

Ocean Circulation and Composition. Initial emphasis will be placed on documenting past changes in oceanic circulation and composition and understanding their relationship to past global climate.

Ocean Productivity. Research that is aimed at reconstructing the historical productivity of oceanic ecosystems and its relationship with past global climate will be performed.

Sea Level Change. The history of changes in sea level will be reconstructed and related to global-scale climate change.

Paleohydrology. Research will be performed to reconstruct past hydrologic conditions – how they varied through time and how they related to climate and responded to climate change. This will include studies of past surface water, ground water, and lake level changes.

Human Interactions

Human Interactions
Data Base Development Models Linking: Population Growth and Distribution Energy Demands Changes in Land Use Industrial Production

Data Base Development. Empirical research on human interactions in global change must be based upon long-term, comparable, cross-national data bases. Among these data bases should be information on land use practices, energy transformations, economic and social behavior, and social attitudes towards and perceptions of environmental change.

Models Linking Population Growth and Distribution, Energy Demands, Changes in Land Use, and Industrial Production. Fundamental research will be carried out to develop a scientific understanding of the relationships and interactions between various types of human activities and global environmental change. This research will serve as the basis for developing models of change over time. Research must deal with the patterns of direct human action or impact on the environment and with the Earth system, e.g., it must deal with both deforestation and the economic system that makes deforestation profitable.

Solid Earth Processes

Coastal Erosion. Studies of coastal erosion and how wetland losses are affected by sea level changes associated with global warming and the associated volume changes of the cryosphere will be conducted. The geologic processes related to land loss and the sediment budget for coastal regions will be also be studied to evaluate coastal erosion and inundation.

Volcanic Processes. The role of subaerial and submarine volcanism in contributing radiatively important gases, aerosols, heat, and fluids that influence the composition of the atmosphere and the ocean will be studied and quantified. Heat flux from submarine volcanism will be evaluated in light of its influence on ocean circulation.

Permafrost and Marine Gas Hydrates. Changes in the areal extent of permafrost will be studied to determine the quantity of radiatively important gases released to the atmosphere. Studies will be conducted to understand how changes in ocean temperature will induce decomposition of the hydrates and release methane.

Solid Earth Processes
Coastal Erosion Volcanic Processes Permafrost and Marine Gas Hydrates Ocean/Seafloor Heat and Energy Fluxes Surficial Processes Crustal Motions and Sea Level

Ocean-Seafloor Heat and Energy Fluxes. Mid-ocean ridge systems will be studied to quantify the flux of heat volatiles and particulates into the ocean that may influence ocean circulation, chemistry, and the CO_2 budget.

Surficial Processes. The erosional, transport, and depositional processes on the Earth's surface will be studied to determine their contributions to land surface changes, such as desertification, that may result in events such as dust storms.

Crustal Motions and Sea Level. Studies of the loading of the Earth's crust and its deformation, both past and present, will be used to establish local versus global absolute sea level change.

Solar Influences

EUV/UV Monitoring. Instrumentation with optimum long-term stability over the solar and magnetic cycles (1 percent in the ultraviolet and 5 percent in the extreme ultraviolet) will be developed and installed. Data will be analyzed with a view to aid the interpretation of ozone density changes.

Atmospheric/Solar Energy Coupling. Studies will be conducted on the energy, momentum, and mass transfer across the boundaries of the sun-Earth system to understand the coupling of energy between atmospheric regions as it relates to the chemistry and dynamics of these regions.

Solar Influences
EUV/UV Monitoring Atm/Solar Energy Coupling Irradiance (Measure/ Model) Climate/Solar Record Proxy Measurements and Long-Term Data Base

Irradiance (Measurements/Models). Observations of total and spectral solar irradiance with high precision (0.01 percent) and stability over the solar cycle will be conducted to improve current understanding through theory and modeling, of the relationships between irradiance, solar variability, and activity. The ground-based observations will be important to biological response studies.

Climate/Solar Record. Modeling of climate response to solar inputs and variability will be made by comparison of modern and paleoclimates using proxy data.

Proxy Measurements and Long-Term Data Base. Studies using modern measurement techniques to determine solar output, including development of proxies for UV and EUV such as 10.7 cm flux, CaK and HeI 10830 spectral lines, will be initiated. A long-term observing program will be maintained and proxy measures for decadal and paleoclimate studies and ozone variability will be derived.

Evaluation Criteria

Within the priority framework, the CES will implement the Program on the basis of the following criteria:

- *Relevance/Contribution.* The research addresses the overall goal and the three key scientific objectives of the Program.
- *Scientific Merit.* The proposed work is scientifically sound and of high priority.
- *Readiness.* The level of planning is high, the capabilities are of high-quality and in place, and the research is likely to produce early advances.
- *Linkages.* National and international programmatic connections, including interagency partnerships, are in place.
- *Costs.* The identified resources are adequate, they represent an appropriate share of total available resources, there are prospects for joint funding, and long-term resource implications have been evaluated.

FY 1989-1990 U.S. Global Change Research Program Budget

FY 1989-1990 Budget Summary

Over the past year, the CES conducted several interagency global change research budget planning and analysis activities to ensure that the President's FY 1990 Budget includes requests that are well integrated and responsive to the Program's goals and priorities.

Table 1 presents the FY 1989-1990 Program budget. In FY 1989, funding for focused global change research activities total $133.9 million. The President's FY 1990 Budget proposes a funding level of $191.5 million for this Program. This budget will allow the focused Program to expand and accelerate its research activities across most areas of global change. As a result of subsequent CES discussions, the levels of effort between science elements have changed slightly since the original strategy document.

FY 1990 Initiatives

Based on the priority framework, the Program has identified several new initiatives for FY 1990. The majority (approximately 85 percent) of the resources allocated to FY 1990 initiatives have been directed toward scientific activities within the three higher priority interdisciplinary science elements; Climate and Hydrologic Systems, Biogeochemical Dynamics, and Ecological Systems and Dynamics. These new initiatives include new programs and augmentations to ongoing efforts. In most cases, the research initiatives contain significant elements of all three scientific objectives, i.e. monitoring, understanding, and predicting global change, and are components of co-ordinated national and/or international programs.

The fact that the FY 1990 initiatives cut across many of the seven science elements and three scientific objectives demonstrates the interdisciplinary and multi-objective nature of the Program. However, this also makes it very difficult to display the individual agency programmatic contributions. Some examples of these agency initiatives will be presented here along with the budget by science element, by agency, and by Federal Budget Function. The following brief section analyzes the characteristics of some examples of the FY 1990 initiatives:

The Department of Commerce/National Oceanic and Atmospheric Administration (NOAA) Radiatively Important Trace Species initiative focuses on Biogeochemical Dynamics, is a single agency program that contains elements of all three science objectives, complements other ongoing U.S. agency programs (primarily in NASA and NSF), and is part of the high priority research outlined in the ICSU International Global Atmospheric Chemistry Programme.

The NSF and DOE Global Ocean Flux Study initiatives focus on Biogeochemical Dynamics, contain elements in all three science objectives, and are key components of a well-coordinated national (NSF, DOE, NASA, NOAA) and international program.

Table 1

U.S. GLOBAL CHANGE RESEARCH PROGRAM BUDGET FOR FISCAL YEARS 1989 AND 1990

(Dollar in Millions)

AGENCY	TOTAL BUDGET		CLIMATE AND HYDROLOGIC SYSTEMS		BIOGEOCHEMICAL DYNAMICS		ECOLOGICAL SYSTEMS & DYNAMICS		EARTH SYSTEM HISTORY'		HUMAN INTERACTIONS		SOLID EARTH PROCESSES		SOLAR INFLUENCES	
	FY89	FY90	FY89	FY90	FY89	FY90	FY89	FY90	FY89	FY90	FY89	FY90	FY89	FY90	FY89	FY90
AGENCY TOTALS	133.9	191.5	37.0	60.2	26.1	38.6	32.5	46.9	3.3	0.0	22.0	20.1	8.9	10.4	4.1	2.3
DOC/NOAA	9.0	20.0	8.5	16.5	0.5	3.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DOE	20.2	27.2	7.0	12.0	6.0	5.5	4.2	7.3	0.0	0.0	2.0	1.2	0.0	0.0	1.0	1.2
DOI *	5.3	11.3	1.8	4.6	0.2	0.3	0.0	0.0	1.3	3.3	1.5	2.5	0.5	0.6	0.0	0.0
EPA	27.4	35.3	0.7	2.2	0.8	3.5	7.4	13.2	0.0	0.0	18.5	16.4	0.0	0.0	0.0	0.0
NASA	14.5	21.5	4.3	6.4	3.0	4.4	4.3	6.4	0.0	0.0	0.0	0.0	2.2	3.3	0.7	1.0
NSF	39.2	53.5	13.2	17.0	13.5	10.3	1.9	1.9	2.0	4.7	0.0	0.0	6.2	6.5	2.4	5.1
USDA	18.3	22.7	1.5	1.5	2.1	3.1	14.7	18.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

* NOTE: FY 1990 Focused Program Total differs from the amount reported in *Our Changing Planet: A U.S. Strategy for Global Change Research* due to budget changes made after the printing date.

The proposed NASA Earth Observing System is a broad-based program that contains elements in all three science objectives, and will contribute towards an improved understanding of five of the seven scientific elements. The Program includes advanced technology definition studies for this future initiative. A significant international contribution has been negotiated through a series of bilateral agreements with the European Space Agency and other nations having major space programs.

The Tropical Oceans and Global Atmosphere (TOGA) program addresses all three scientific objectives of the U.S. Global Change Research Program. It addresses an important problem in climate prediction, incorporating large-scale observations, intensive process research, and work on predictive models. In the U.S., TOGA involves formally coordinated work by four agencies (NOAA, NSF, NASA, and the Department of Defense [DOD]) advised by a panel from the NAS. Internationally, as part of the WCRP, 16 nations are cooperating through an intergovernmental board formally established for TOGA implementation. Several important bilateral relationships, which involved the U.S., have also been established to support TOGA.

The DOE Carbon Dioxide Program will initiate focused research on the problem of early detection of global climate change. This initiative seeks to identify the atmospheric and other measurements that appear promising in providing the early warming signal and to develop the analytical methodologies for quantifying the links between the "greenhouse" gas increases and climate change. The initiative spans the first two science elements and will examine the cause and effect relationships involved in global warming.

The National Ozone Expedition is an interagency program (NASA, NOAA, NSF) designed to obtain an improved understanding of the seasonal stratospheric ozone depletion over Antarctica and the biological significance of the resultant changes in ultraviolet radiation reaching the surface of this region of the Earth. Increased monitoring of solar ultraviolet fluxes in Antarctica will be initiated by NSF to help meet the program's objectives.

Budget by Science Element

From the scientific perspective, the best way to understand the Program budget is to examine it by science element. Figure 12 presents the FY 1989 and FY 1990 budgets by science element for focused research efforts.

- *Climate and Hydrologic Systems.* The FY 1990 budget proposes $60.2 million for this element, a 63 percent increase over the FY 1989 level. This increased level of effort will primarily focus on monitoring, understanding, and predicting aspects of (i) ocean circulation through tracer experiments (NOAA and NSF), (ii) interactions between the tropical oceans and the global atmosphere (NSF), (iii) sea level (NOAA), (iv) the exchange of energy and water between the atmosphere and terrestrial ecosystems and the cryosphere (NSF, Department of the Interior/United States Geological Survey [USGS], and NOAA), (v) the quantitative links between radiativechange and climate change (DOE), and advanced space remote-sensing technology (NASA).

- *Biogeochemical Dynamics.* The FY 1990 budget proposes $38.6 million for this element, a 48 percent increase over the FY 1989 level. This increased level of effort will primarily focus on monitoring, understanding, and predicting aspects of (i) the fluxes of radiatively important trace gases between the atmosphere and the oceans and terrestrial ecosystems (USGS, NSF, NOAA, EPA, USDA), (ii) fluxes of nutrients and carbon within the oceans (NSF, DOE), (iii) transformations, distributions and trends of trace species within the upper and lower atmosphere (NOAA, NSF), and development of advanced space remote-sensing technology (NASA).

- *Ecological Systems and Dynamics.* The FY 1990 budget proposes $46.9 million for this element, a 44 percent increase over the FY 1989 level. This increased level of effort will primarily focus on understanding (i) the response of managed and unmanaged ecosystems to changes in climate, carbon dioxide, ultraviolet radiation and other stress factors (USDA, EPA, DOE); and development of advanced space remote-sensing technology (NASA).

- *Earth System History.* The FY 1990 budget proposed $8.0 million for this element, more than doubling the FY 1989 level. This modest increased level of effort will focus on an improved reconstruction of certain aspects of the Earth's past climates and environments (USGS, NSF).

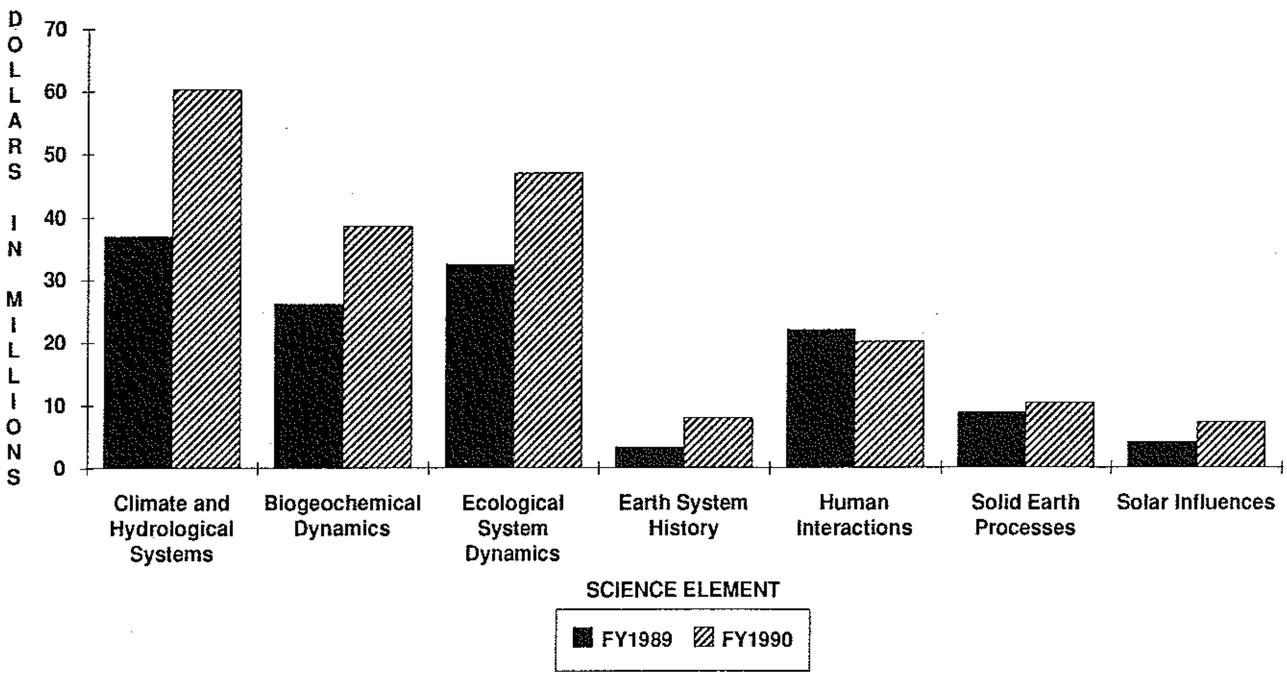


Figure 12. U.S. Global Change Research Program Budget by Science Element

- *Human Interactions*. The FY 1990 budget proposed $20.1 million for this element. While the budget table indicates no new FY 1990 resources for Human Interactions, NSF and USGS will augment efforts in the development of land surface data systems, and on understanding the relationships among global environmental change and human activities, through a reprogramming of existing funds in FY 1990.

- *Solid Earth Processes*. The FY 1990 budget proposes $10.4 million for this element, a 17 percent increase over the FY 1989 level. This increased level of effort will primarily focus on observations and understanding of crustal motions and dynamics (NSF), and developing advanced space remote-sensing technology (NASA).

- *Solar Influences*. The FY 1990 budget proposes $7.3 million for this element, a 78 percent increase over the FY 1989 level. This increased level of effort will primarily focus on monitoring solar ultraviolet fluxes in Antarctica (NSF); understanding and predicting the solar driven energetics and dynamics of atmospheric regions (NSF, DOE); and developing advanced space remote-sensing technology for monitoring and understanding the influences of solar processes on the Earth's environment (NASA).

Budget by Agency

Figure 13 shows the FY 1989 and FY 1990 proposed focused program budgets by agency. The individual agency efforts reflect their particular mission, and build upon their respective scientific and technical strengths.

- *Department of Commerce/National Oceanic and Atmospheric Administration (DOC/NOAA)*. DOC/NOAA programs emphasizes improving predictions of climate change and its regional implications. The FY 1990 budget proposes $20.0 million for DOC/NOAA, roughly doubling the FY 1989 level.

- *Department of Energy (DOE)*. DOE maintains a research program directed at the impact of energy production and use on the global Earth system. The DOE programs are focused primarily on climate and ecosystem response research. The FY 1990 budget proposes $27.2 million for DOE, a 35 percent increase over the FY 1989 level.

- *Department of the Interior/United States Geological Survey (DOI/USGS)*. DOI/USGS carries out research in past climate change, regional hydrology, the carbon cycle, coastal erosion, volcanic activity, and glaciology. The FY 1990 budget proposes $11.3 million for DOI/USGS, roughly doubling the FY 1989 level.

- *Environmental Protection Agency (EPA)*. EPA research is focused on ecological systems and human interactions. The FY 1990 budget proposes $35.3 million for EPA, a 29 percent increase over the FY 1989 level.

- *National Aeronautics and Space Administration (NASA)*. NASA conducts Earth science research from space. This research effort supports advanced technology definition studies for the proposed Earth Observing System (Eos). These studies focus on defining the sensors, platforms, and data management needed to study a broad range of global change processes from space. The FY 1990 budget proposes $21.5 million for NASA, a 48 percent increase over the FY 1989 level.

- *National Science Foundation (NSF).* The NSF primarily supports university-based basic research in all areas of global change. The FY 1990 budget proposes $53.5 million for NSF, a 36 percent increase over the FY 1989 level.

- *United States Department of Agriculture (USDA).* USDA research deals with the impact of climate on agricultural and ecological systems and the impact of these systems on the climate. The FY 1990 budget proposes $22.7 million for USDA, a 24 percent increase over the FY 1989 level.

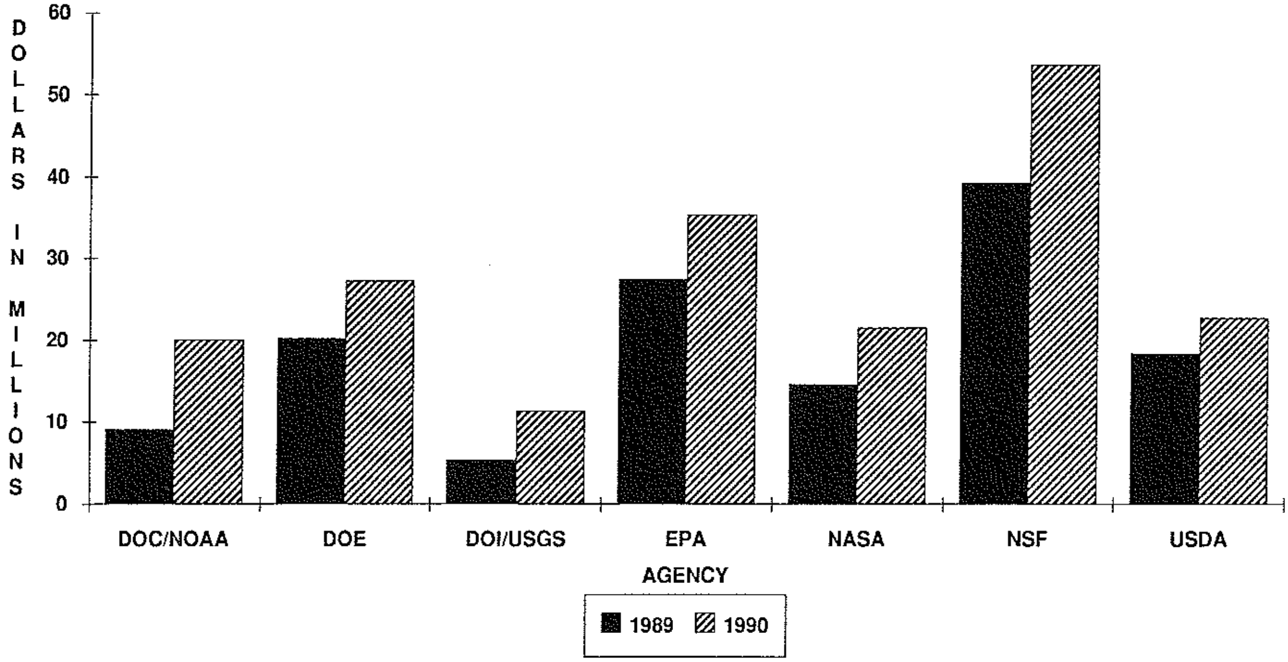


Figure 13. U.S. Global Change Research Program Budget by Agency

Budget by Federal Budget Function

Scientific, environmental, energy, and agricultural resources are very important to the Nation. All either impact or are impacted by global change.

Figure 14 and Table 2 illustrate the Program's focused funding levels by the Federal budget functions that encompass these national resources. As would be expected, the budget proposes significant increases for budget functions 250 (General Science, Space, and Technology) and 300 (Natural Resources and Environment). In FY 1990, $75 million is proposed for function 250, a 40 percent increase over FY 1989. For function 300, $66.6 million is proposed for FY 1990, a 60 percent increase over FY 1989.

Despite the broad distribution across these budget functions and, hence, across many Executive Branch and Congressional decision making paths, it is crucial to view the Program as a single, integrated research effort. The success of many of the science objectives is dependent on the cooperation and contributions of all the individual agency programs. Thus, decisions concerning these investments should attempt to recognize the full scope and structure of the U.S. Global Change

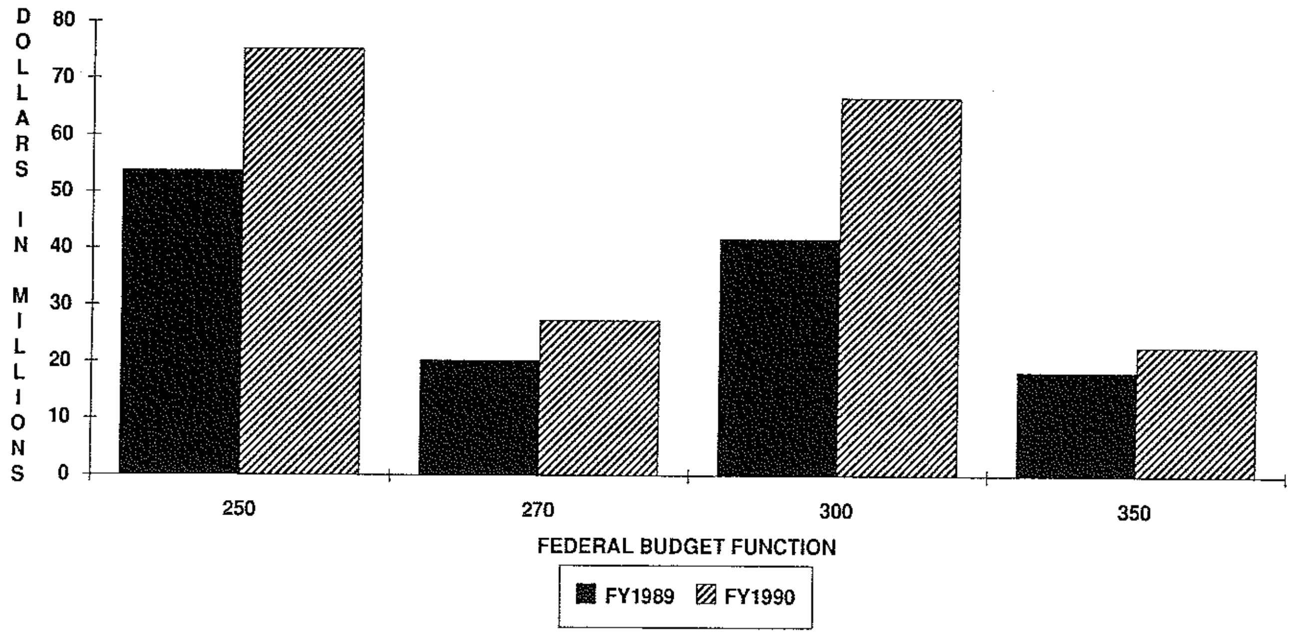


Figure 14. U.S. Global Change Research Program by Federal Budget Function.

Table 2

U.S. GLOBAL CHANGE RESEARCH PROGRAM BUDGET

by Federal Budget Function for Fiscal Years 1989 and 1990
(Dollars in Millions)

Budget Function	Budget Function Number	1989	1990
Total		133.9	191.5
General Science, Space and Technology	250	53.7	75.0
NASA		14.5	21.5
NSF		39.2	53.5
Energy (DOE)	270	20.2	27.2
Natural Resources & Environment	300	41.7	66.6
DOI/USGS		5.3	11.3
EPA		27.4	35.3
DOC/NOAA		9.0	20.0
Agriculture (USDA)	350	18.3	22.7

APPENDIX A

Agency Roles in Addressing the Specific Goals and Objectives of the U.S. Global Change Research Program

General statements of individual agency roles in addressing the specific goals and objectives of the U.S. Global Change Research Program have been developed. These role statements identify roles in the context of that Program and should not be interpreted as representing the full suite of agency responsibilities and activities in all of Earth sciences. The statements were designed to be brief summaries of agency involvement in the Program and specific mention of a task or geographic region does not imply exclusive responsibility.

Department of Commerce - National Oceanic and Atmospheric Administration

NOAA maintains a balanced program of observations, analytical studies, climate prediction and information management in the national global change program. NOAA will be responsible for: operational *in situ* and satellite observations and monitoring programs; mission-directed research on physical and biogeochemical processes in the climate system (including their effect on marine ecosystems and resources); development, testing, and application of models and diagnostic techniques for the detection and prediction of natural and human-induced climatic changes; and the acquisition, maintenance, and distribution of long-term data bases and related climate information.

Department of Defense

DOD conducts mission-related research into environmental processes and conditions that affect defense operations, tactics, and systems. DOD research programs contribute information that is useful in focused global change programs of other agencies; other agencies' programs similarly produce results that are useful to DOD's mission-related research programs. DOD participates in global change program planning and collaborates with other agencies in global change data management in order to ensure effective coordination and transfer of information between DOD and civilian agency programs.

Department of Energy

DOE shall conduct research on carbon dioxide and other emissions from energy supply and end use systems. The research shall include the climate's response to those emissions and shall develop the base of scientific information necessary to assess the climate's response assuming various energy and industrial policies. Associated efforts may include, but not be limited to, research to quantify the relationships between carbon dioxide and other trace gases and temperature rise, assessment and application of predictive models, evaluation of global and regional climate and environmental responses to various energy policy options, and research on industrial sources of trace gases. Research may include all causes of climate change and how possible responses to change could affect energy options.

Department of the Interior

DOI program efforts address the collection, maintenance, analysis, and interpretation of short- and long-term land, water, biological, and other natural resource data and information. Such efforts include, but are not limited to, monitoring of hydrologic and geologic processes and resources, land use, land cover, and biological habitats, resources, and diversity. Some DOI research areas include: past global change recorded in the physical, chemical, and biological record; the hydrologic cycle; land-surface and solid Earth processes that relate to environmental change; geography and cartography;

polar and arid region processes; ecosystem modeling and dynamics; resource ethnology. The Department utilizes knowledge developed in these and other agencies' programs to evaluate and when necessary respond to potential effects of global change on water, land, biological, and other natural resources.

Department of Transportation

DOT maintains awareness of the impact of transportation on global change. That impact occurs primarily through the use of fuels in transportation systems, resulting in the emission of combustion gases, including aircraft emission, into the stratosphere. DOT must also be aware of how climate changes affect the efficiency and safety of transportation on land, sea, rivers, and in the air.

Environmental Protection Agency

EPA conducts research to assess, evaluate and predict the ecological, environmental, and human-health consequences of global change, including the feedback of these systems on climate change. Additional areas of activity include research to determine emission factors, and inventories and models for radiatively important trace gases, and research to predict the interactions between global atmospheric change and regional air and water quality.

National Aeronautics and Space Administration

NASA is responsible for Earth science research from space, including those studies of broad scientific scope that study the planet as an integrated whole. Associated efforts include related process studies; sub-orbital and ground-based studies; remote-sensing and advanced instrument development; improvement of techniques for the transmission, processing, archiving, retrieval, and use of data; related scientific models; and other research activities in atmospheric, oceanographic, and land sciences.

National Science Foundation

NSF is responsible for maintaining the health of basic research in all areas of Earth, atmospheric (including solar-terrestrial), and ocean sciences, including the relevant biological and social sciences and research in the polar regions. The basic research program is focused on ground-based studies on regional and global scales; large-scale field programs; interpretation and use of remotely sensed data and geographic information systems; theoretical and laboratory research; research facilities support; and the development of the numerical models, information and communication systems, and data bases.

United States Department of Agriculture

USDA conducts research to assess the effects of global change on the agricultural food and fiber production systems and on forests and forest ecosystems of the U.S. and world wide; including, but not limited to, basic research on the biological response mechanisms to increasing greenhouse gases, improvement of plant and animal germplasm to respond to global change, and development and implementation of plans for terrestrial mitigation systems to ameliorate the observed increases of greenhouse gases, including crops and forests. An additional responsibility shall include research on applications of agricultural climatology to improve management decisions and conservation of resources, while maintaining quality and quantity of crop yields.

APPENDIX B

The Current U.S. Global Change Research Program

Cross-Cutting Program Characteristics

Although the U.S. Global Change Research Program uses the seven interdisciplinary science elements as its organizing structure, two other cross-cutting characteristics — type of science activity and focused versus contributing programs — are also important indicators of Program activities. Their utility and role in the Program are summarized here. To provide the perspective that these other indicators yield, the FY 1989 agency programs are described below in terms of these two characteristics.

Science Activities and Infrastructure. While the interdisciplinary science elements (e.g., Biogeochemical Dynamics) broadly define the nature of the scientific disciplines involved, the overall program can also be described by the following four types of science activities and infrastructure:

- research,
- long-term observations,
- data management, and
- facilities.

In FY 1989, as the agencies worked toward establishing the Program, the above crosscut was the format of intercomparison, both in the science and budget activities. The utility to the Program of having these four categories as a crosscut lies in the fact that they generally (i) involve separate parts of the science community, (ii) require different styles of execution and hence program planning, and (iii) occur with different emphases within the missions of the agencies (see Appendix A) and necessitate a spectrum of budgetary approaches. Some characteristics of each type of activity, described below, illustrate these points:

Research. This crosscut activity includes:

- *laboratory studies* of the basic processes involved in environmental systems,

- *field measurement campaigns and satellite missions* focused on particular phenomena or problems, and

- *theory, analysis, modeling, and prediction* of processes and Earth system components.

Implicit in the first two is the development of advanced instrumentation, which often is the limiting aspect of such activities. The last item includes operational forecasting models, as well as models of human activities that force global change. Similarly, implicit in all three is their role in assessments of the state of the science of global change or its components.

Examples include laboratory studies of biological processes, ice-coring campaigns, and the development of coupled atmosphere/ocean general circulation models, and the analysis of demographic trends of "sunbelt" relocation.

Long-Term Observations. This activity includes observations made periodically or continuously for time periods of a few years or more to document global change. It includes the facilities to support these observations, such as special sites, as well as the time and costs of taking the measurements, developing the algorithms to reduce the raw data, and analyzing the results.

Examples include the field observations, satellite measurements, and analysis of the changes in the concentrations of trace gases; defining the variations and trends in global atmospheric circulation; observing weather patterns and ocean parameters from space; measuring streamflow, groundwater levels, and lake levels; and recording ecological changes within special watersheds.

Data Management. This activity includes organizing, validating, archiving, preserving, and making available data for global change research. The process goes far beyond simply archiving and dissemination and involves analysis and decisions regarding data compression, retention periods, and media appropriateness. This category is so often neglected in large-scale programs that it is treated as a stand-alone topic above in this document. (See the section on "Data Management.")

Examples include meteorological and oceanographic data "products," bulletins on sporadic geophysical phenomena like volcanic eruptions, sunspot records, satellite data banks, land use records, and industrial production data.

Facilities. These are the major hardware items that support many of the global change research activities. They represent substantial one-time investments, as well as additional maintenance and operational costs.

Examples include research ships, field facilities, supercomputers, telecommunication hardware and software, radioisotope dating laboratories, and aircraft.

All of the above are crucial to progress in understanding global change and its regional impacts. Indeed, all four generally are involved in the large-scale mission-oriented programs aimed at characterizing some specific feature of global change. Numerous other examples abound, demonstrating that while some of the elements are more visible that others (compare aircraft and data management), it would be a folly to promote one at the expense of the other (e.g., to fail to invest in modernization of the oceanic research vessel fleet because of the relatively large one-time cost).

Focused Versus Contributing Programs

The U.S. Global Change Research Program is intended as a coordinated and interconnected research effort that advances our understanding of the global environment. The categories of activity are further divided into "Focused"and "Contributing" programs. In the report *Our Changing Planet: A U.S. Strategy for Global Change Research* and in this Research Plan the following definitions have been used by the Federal Agencies for the FY 1989 and the FY 1990 Budget summaries.

A *focused* program is defined as an agency program or activity designed specifically to study global environmental changes or global processes which constitute part of the Earth's environmental system. For example, NSF's Global Geosciences Program, NOAA's Climate and Global Change Program, NASA's proposed Earth Observing System satellite program, and EPA's proposed Global Climate Change Research Program are defined as "focused" programs.

A *contributing* program is an activity which was established and primarily justified on a basis other than the specific study of global change, but which has the potential to contribute substantially to global change research. Examples of "contributing" activities are ongoing agency programs such as the NSF's Ocean Drilling Program and Atmospheric Chemistry Program, NOAA's weather satellite program and ocean-atmosphere data set, USGS's stream gauge program, and NASA's TOPEX/Poseidon and Upper Atmosphere Research Satellite programs. In many, but not all, cases the contributions of these programs can only be realized by extracting global change information from their traditional products and results. Contributing programs are included in the global change crosscut in order to present a comprehensive picture of the broad agency capabilities in the area of global change.

As the agencies proceed to define their global change programs in FY 1991 and subsequent years, the CES has agreed to redefine focused and contributing programs as follows: A focused program is an agency program, activity, or new initiative which addresses the explicit goals and objectives of the U.S. Global Change Research Program. A contributing program is an activity or new initiative which primarily is justified on a basis other than the specific study of global change but which contributes substantially to the goals and objectives of the U.S.Global Change Research Program. Therefore, in FY 1991 and subsequent years, only the following activities identified in the above paragraphs would be identified as contributing, the NSF's Ocean Drilling Program, NOAA's weather satellite program, and USGS's stream gauge program, all the other identified activities will be classified as focused, e.g., NASA's TOPEX/Poseidon and Upper Atmosphere Research Satellite programs and NSF's Atmospheric Chemistry Program.

Table B-1 presents the FY 1989-1990 Program budget. In FY 1989, funding for focused and contributing global change research activities total $133.9 and $1476.2 million, respectively. The President's FY 1990 Budget proposes a funding level of $191.5 and $1411.8 million for focused and contributing activities in this Program. This budget will allow the focused Program to expand and accelerate its research activities across all areas of global change. As a result of subsequent CES discussions, the levels of effort between science elements has changed slightly since the original strategy document. As reflected in the supportive nature of these programs, the FY 1990 contributing program decreased as the result of decisions beyond the scope of the Program.

Description of Current Agency Programs

The following pages present a description of the current (FY89) focused and contributing activities for the eight agencies (listed below) involved in global change research.

- Department of Commerce (DOC) – National Oceanic and Atmospheric Administration (NOAA).
- Department of Defense (DOD).
- Department of Energy (DOE).
- Department of the Interior (DOI).
- Environmental Protection Agency (EPA).
- National Aeronautics and Space Administration (NASA).
- National Science Foundation (NSF).
- United States Department of Agriculture (USDA).

Table
U.S. GLOBAL CHANGE RESEARCH PROGRAM
(Dollars in

AGENCY	TOTAL BUDGET		CLIMATE AND HYDROLOGIC SYSTEMS		BIOGEOCHEMICAL DYNAMICS	
	FY89	FY90	FY89	FY90	FY89	FY90
AGENCY TOTALS	1610.9	1603.3	834.8	797.8	241.6	250.0
FOCUSED	133.9	191.5	37.0	60.2	26.1	38.6
CONTRIBUTING	1476.2	1411.8	797.8	737.6	215.5	211.4
DOC/NOAA						
FOCUSED	9.0	20.0	8.5	16.5	0.5	3.5
CONTRIBUTING	442.1	382.8	433.3	374.0	7.7	7.7
TOTAL	451.1	402.8	441.8	390.5	8.2	11.2
DOD						
FOCUSED	0.0	0.0	0.0	0.0	0.0	0.0
CONTRIBUTING	45.7	32.3	31.4	20.5	2.1	1.7
TOTAL	45.7	32.3	31.4	20.5	2.1	1.7
DOE						
FOCUSED	20.2	27.2	7.0	12.0	6.0	5.5
CONTRIBUTING	46.5	46.5	0.0	0.0	31.1	31.1
TOTAL	66.7	73.7	7.0	12.0	37.1	36.6
DOI*						
FOCUSED	5.3	11.3	1.8	4.6	0.2	0.3
CONTRIBUTING	210.9	204.5	90.6	92.9	1.2	0.9
TOTAL	216.2	215.8	92.4	97.5	1.4	1.2
EPA						
FOCUSED	27.4	35.3	0.7	2.2	0.8	3.5
CONTRIBUTING	70.0	58.9	13.9	11.8	3.7	2.6
TOTAL	97.4	94.2	14.6	14.0	4.5	6.1
NASA						
FOCUSED	14.5	21.5	4.3	6.4	3.0	4.4
CONTRIBUTING	399.2	412.6	178.3	184.8	147.0	142.5
TOTAL	413.7	434.1	182.6	191.2	150.0	146.9
NSF						
FOCUSED	39.2	53.5	13.2	17.0	13.5	18.3
CONTRIBUTING	112.4	120.0	42.2	46.7	18.0	20.0
TOTAL	151.6	173.5	55.4	63.7	31.5	38.3
USDA						
FOCUSED	18.3	22.7	1.5	1.5	2.1	3.1
CONTRIBUTING	149.4	154.2	8.1	6.9	4.7	4.9
TOTAL	167.7	176.9	9.6	8.4	6.8	8.0

*NOTE: FY 1990 Focused Program Total differs from the amount reported in *Our Changing Planet: A U.S. Strategy for Global Change Research* due to budget changes made after the printing date.

B-1
BUDGET FOR FISCAL YEARS 1989 AND 1990
Millions)

ECOLOGICAL DYNAMICS		EARTH SYSTEM HISTORY		HUMAN INTERACTIONS		SOLID EARTH PROCESSES		SOLAR INFLUENCES	
FY89	FY90	FY89	FY90	FY89	FY90	FY89	FY90	FY89	FY90
188.4	193.1	31.5	38.8	116.9	110.5	176.5	191.1	20.4	22.0
32.5	46.9	3.3	8.0	22.0	20.1	8.9	10.4	4.1	7.3
155.9	146.2	28.2	30.8	94.9	90.4	167.6	180.7	16.3	14.7
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.1	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.1	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11.2	5.2	0.0	0.0	0.0	0.0	1.0	4.9	0.0	0.0
11.2	5.2	0.0	0.0	0.0	0.0	1.0	4.9	0.0	0.0
4.2	7.3	0.0	0.0	2.0	1.2	0.0	0.0	1.0	1.2
8.3	8.3	0.4	0.4	0.0	0.0	6.7	6.7	0.0	0.0
12.5	15.6	0.4	0.4	2.0	1.2	6.7	6.7	1.0	1.2
0.0	0.0	1.3	3.3	1.5	2.5	0.5	0.6	0.0	0.0
36.6	34.9	0.6	0.3	68.1	63.7	11.8	9.8	2.0	2.0
36.6	34.9	1.9	3.6	69.6	66.2	12.3	10.4	2.0	2.0
7.4	13.2	0.0	0.0	18.5	16.4	0.0	0.0	0.0	0.0
52.4	44.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
59.8	57.7	0.0	0.0	18.5	16.4	0.0	0.0	0.0	0.0
4.3	6.4	0.0	0.0	0.0	0.0	2.2	3.3	0.7	1.0
13.8	16.7	4.5	5.5	0.6	0.0	47.3	55.7	7.7	7.4
18.1	23.1	4.5	5.5	0.6	0.0	49.5	59.0	8.4	8.4
1.9	1.9	2.0	4.7	0.0	0.0	6.2	6.5	2.4	5.1
12.9	15.7	22.0	24.2	1.0	1.4	9.7	6.7	6.6	5.3
14.8	17.6	24.0	28.9	1.0	1.4	15.9	13.2	9.0	10.4
14.7	18.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19.6	19.8	0.7	0.4	25.2	25.3	91.1	96.9	0.0	0.0
34.3	37.9	0.7	0.4	25.2	25.3	91.1	96.9	0.0	0.0

Department of Commerce (DOC): National Oceanic and Atmospheric Administration (NOAA)

Climate and Hydrologic Systems

Focused ($8.5M)

Research

• *Interannual Climate (TOGA).* NOAA proposes to continue strong lead agency role in the multi-agency, international Tropical Ocean and Global Atmosphere (TOGA) program. NOAA's contributions derive from: (i) a coordinated ocean-atmosphere measurement program; (ii) intensive, short-term, regional measurements focused on specific processes identified as critically important for an understanding of large-scale atmosphere-ocean interaction; (iii) empirically-based descriptive and statistical studies; and modelling efforts. The long-range goal is to achieve an operational predictive capability with the more immediate aim of establishing the limits of predictability of the coupled atmosphere-ocean system.

Observations

• *Ocean Monitoring.* NOAA's contribution to the national effort to obtain an effective description of the time-dependent global ocean includes: using established techniques such as drifting and moored buoys, coastal and island stations, and volunteer observing ships. The goal is to measure continuously, and on a long-term, global basis, an appropriate set of ocean parameters that are affected by or influence seasonal to decadal changes in the Earth's climate system. In addition, this program element involves the development and application of new techniques, such as freon tracer studies of water mass formation and movement. These activities will improve model simulations of climate relevant ocean behavior and our ability to predict long-term climatic change.

• *Global Sea Level.* A separate monitoring effort will concentrate specifically on the measurement of global sea level. NOAA will establish a globally distributed, *in situ* network capable of measuring absolute sea level to 1 cm accuracy by making use of existing systems where possible, by deploying new high technology systems at selected sites, and by establishing and integrating a global absolute geodetic reference framework. The data from this *in situ* network will be combined with satellite altimetric observations (initially from GEOSAT) to produce a global absolute sea level monitoring capability. Near and long-term benefits include detection of actual sea level changes and improved understanding of global ocean dynamics.

• *Climate Monitoring and Diagnostics.* The goal of this program element is to accurately observe the climate state on a global basis, to determine the fluctuations and trends with confidence, and to examine potential changes in the future. Specific activities under the Climate and Global Change Program include: (i) Climate Data Assimilation - the step-wise development of improved quality control and data inventory leading to an operational project for routine post analysis of meteorological data for climate purposes; (ii) "Reanalysis" Working with other agencies and the academic community to define and implement a meaningful program in "reanalysis" -- the retrospective analysis of routine oceanographic and meteorological data after the addition of delayed data, satellite data products and research data; (iii) Satellite Data Projects - To provide integrated, descriptions of the climate system including the atmosphere, land surface, ocean surface, and elements of the cryosphere; based primarily on data from NOAA's polar-orbiting and geostationary platforms, along with appropriate surface analyses; and (iv) Climate Diagnostics - The application of mathematical and statistical analysis of climate data sets to assess the evolution of climate trends and fluctuations and to examine potential changes in the future. Near and long-term benefits of this information include predictive model improvements and the ability to detect, document, and assess climate change.

Data Management

• *Climate Data Services.* To support activities which lead to climate data bases, data sets, and data fields which meet user requirements and can be easily accessed by the global change community. This element addresses data management support for NOAA-specific Climate and Global Change programs as well as NOAA's contribution to cooperative efforts with other agencies to define and develop data systems to support a national global change program. Specific activities will include: (i) support for long-term planning mechanisms (including the Interagency Working Group on Data Management for Global Change), (ii) improvements to existing quality-control, processing and communications systems, (iii) system specification and development for long-term data management capabilities, (iv) creation of catalogs, inventories, and directories of environmental data sets, (v) development, maintenance and dissemination of critical climate and global change data bases, and (vi) coordination of processing techniques/procedures as well as hardware/software.

Contributing ($433.3M)

Research

• *Interannual Climate Research, including TOGA.* Understanding the El Niño-Southern Oscillation (ENSO) phenomenon as a major mode of interannual climate variability is the focus of NOAA seasonal and interannual research. This research focuses on the requirements for improving the accuracy, timeliness, and utility of projections of the low frequency climate variations associated with the Southern Oscillation. High priority is given to research for data acquisition and analyses which contribute to the development of a real-time modeling capability and the interpretation of ENSO-related variability. Near and long-term benefits include providing advisories and projections of climate variations associated with ENSO-related changes and improvements in coupled ocean-atmosphere models.

• *Long-Term Climate Research.* In addition to the RITS/CO_2 (Biogeochemical Dynamics) and GMCC (Observation) programs, and climate modeling at GFDL, NOAA's long-term climate research programs also include studies of how ocean dynamics and processes affect long-term climate variability. These activities, like the Subtropical Atlantic Climate Studies (STACS) as well as freon tracer studies to determine the oceans behavior as a source of and sink for carbon dioxide, complement the ocean-atmosphere studies described previously in the context of interannual climate variability. Near and long-term benefits include model improvements and enhanced predictive capabilities.

• *Climate Analysis and Modeling* - at Environmental Research Laboratories (primarily Geophysical Fluid Dynamics Laboratory). The purpose of climate-related modeling research is twofold: to describe, explain and simulate climate variability on timescales from seasons to millennia; and to evaluate the climatic impact of human activities such as the release of CO_2 and other gases in the atmosphere. Available observations are analyzed to determine the physical processes by which the circulations of the oceans and atmospheres are maintained and mathematical models are constructed to study and simulate the ocean, the atmosphere, the coupled ocean, atmosphere and cryosphere system. This work is closely coordinated with operational forecasting requirements at the National Meteorological Center (NMC) and complementary research conducted by the nation's universities and NSF with the ultimate goal of improving our ability to predict changes in the global climate system.

• *Climate Analysis and Prediction* at the National Weather Service/Climate Analysis Center (CAC) : A combined operational and research effort with a primary mission to monitor short-term climate anomalies in near-real-time, perform diagnostics and issue climate outlooks. The major program thrusts include: atmospheric diagnostics emphasizing the global influence of tropical oceans; global climate monitoring using conventional observations with satellite products; ocean modeling for the analysis and prediction of interseasonal and interannual climate variations; stratospheric analysis and trends in ozone; applied climatology and the use of climate information for agriculture, energy applications and water resources; and climate prediction on the weekly, monthly and seasonal time scales. Near-term benefits include a variety of climate information and products distributed for immediate use by government, industry, and research institutions; long-term benefits derive from improvements in routine, operational predictions of climate change and its regional implications.

Observations

• *Long-Term Climate Studies* -- GMCC. The Geophysical Monitoring for Climate Change (GMCC) Program plans and conducts world-wide trace element monitoring programs and research necessary to measure long-term global trends in atmospheric constituents and properties likely to produce change. This approach includes trace gas and particulate measurements, including continuous ground level measurements of carbon dioxide (in collaboration with DOE), solar radiation, ozone, dust loading, vertical distribution of atmospheric particulates, condensation nuclei concentration, and composition of particles relevant to climatic change and analysis of monitoring data to determine global budgets, sources, sinks and trends. Near and long-term benefits include detection of change, documentation of trends and model improvement and verification.

• *Large-Scale Ocean Observations.* To maintain basic ocean data collection, monitoring, and analysis capabilities aimed at improving the ability to predict the behavior of and changes in the global ocean environment. These oceanographic and meteorological data are used in operational forecasts and warnings to also promote safety and economy. In the long-term, these measurements will improve model simulations of climate-relevant ocean behavior and our ability to predict long-term climatic changes.

• *Geodosy.* Processing satellite altimetry data from GEOSAT to produce: time series of sea level, global mesoscale eddy statistics, improved tide models, surface circulation information, and wind speed and height. In addition, NOAA supports a small base program designed to develop a pilot network of "absolute" sea level stations using Global Positioning Systems (GPS) and Very Long Baseline Interferometry (VLBI) techniques. Near-term benefits include support for research programs like TOGA with eventual contributions to a global system for the detection of sea level change.

• *Environmental Satellite Programs.* This activity includes the NOAA series of Polar-Orbiting Environmental Satellites (POES) which monitor weather and surface conditions over the entire globe; the Geostationary Operational Environmental Satellites (GOES) which permit near-continuous observations of the Earth's western hemisphere to provide imagery, soundings, and data collection communication relays from remote data collection platforms; and commercialization of the Land Remote Sensing System (Landsat). NOAA controls the satellites, acquires, processes, and analyzes the satellite data, prepares products, and distributes the products to the National Weather Service and other users. With the application of focused program resources, these products can be converted in the near-term into information useful in detecting and documenting changes in the global environment; and (ii) improving predictive models.

Data Management

• *Long-Term Data Management.* To provide long-term support to the archiving of data for global change; ensure that the integrity of data processes (e.g., observation and quality control, leading up to the archiving of these data) are compatible with the archiving process; and ensure that the archived data are accessible to the user community. By supporting both the NOAA and national programs, these data management activities will provide near and long-term contributions to detecting, documenting, understanding and predicting changes in the global environment.

• *Climate Record Construction* - Comprehensive Ocean-Atmosphere Data Set (COADS): Description of the ocean climate of the past 130 years based on over 100 million individual marine observations beginning in 1853. NOAA continues to be involved in similar climate record construction studies including: a measure of historical tropical rainfall using highly reflective cloud frequency over the tropics, a time-series estimate of stratospheric aerosol loading, and atmospheric data for describing the Northern Hemisphere land climate for the period 1850-1980 (assembled for DOE). Activities such as these allow for model verification and improvements as well as providing for the long-term documentation of change.

Facilities

• *Facilities Support (Ships and Aircraft).* This program element reflects the costs associated with the management, coordination, scheduling and operation of NOAA ships and aircraft in support of climate research primarily.

Biogeochemical Dynamics

Focused ($0.5M)

Long-Term Observations

• *Stratospheric Monitoring.* To obtain reliable, long-term observations of the stratospheric constituents and parameters that are sensitive indicators of stratospheric change and to couple these data with developing theory to understand such changes. Working with NASA, NOAA will establish and operate a monitoring network that uses state-of-the-art, ground-based, remote-sensing instruments to measure several key stratospheric constituents (ozone, temperature, chlorine monoxide, water vapor, aerosols, nitrogen dioxide and hydrochloric acid). Near-term benefits include reliable satellite sensor calibration, and model validation and diagnostics; in the long-term, time-series data will permit detection of trends and documentation of trends.

Contributing ($7.7M)

Research

• *Stratospheric Ozone Processes.* Research on the photochemical processes that control the amount of ozone in the stratosphere. To allow reliable predictions of the current and future impact of natural and man-made chemicals (notably those containing chlorine) on the ozone layer. Approach is an interactive combination of field measurement campaigns (ground-based, aircraft, and balloons), laboratory studies of chemical reactions, and multidimensional theoretical modeling. Near and long-term benefits include predictive model improvements and the differentiation of natural and human-induced changes.

• *Acid and Oxidant Processes.* To develop a predictive understanding of the oxidizing capacity of the global lower atmosphere, which determines how natural and man-made emissions are transformed into compounds, such as acids, that can then be removed from the atmosphere. Part of a multi-agency effort (NOAA, NSF, NASA), NOAA focuses on natural emissions, clear-air chemistry, and dry deposition processes. Understanding is sought via comparisons of results from field studies in continental and oceanic areas and theoretical predictions. Near and long-term benefits include predictive model improvements and the differentiation between natural and human-induced change.

• *Trace gas studies (RITS and CO_2).* To improve measurements, understanding, and eventual prediction of changes in the concentration of radiatively important atmospheric trace gases, such as CH_4 and middle-atmosphere ozone, that affect climate change. Activities (both research and observations) include upgrading the number and accuracy of global measurements, implementing measurements of new trace gases, determining the relationship between natural and anthropogenic sources, analyzing and modeling photochemical and transport processes, and modeling the potential of the radiatively important trace gases to alter the Earth's habitability via the "greenhouse" effect. Near and long-term benefits include predictive model improvements, documentation of change, and differentiation between natural and human-induced change.

Observations

• *Acidic Deposition Monitoring.* In collaboration with several agencies, NOAA operates three types of acidic deposition monitoring sites: (i) dry deposition in the northeastern U.S., (ii) wet deposition in the continental U.S., and (iii) background wet deposition in remote areas of the world (done solely by NOAA). Continuous time-series data will permit detection of change, documentation of trends, and verification of the effect of pollution controls.

Ecological Systems and Dynamics

Contributing ($1.1M)

Observations and Data Management

• *Fisheries Resources Information.* National Marine Fisheries Service base activities related to the effects of climate changes on fisheries. These activities are concentrated in two NMFS laboratories, the Atlantic Environmental Group and the Pacific Environmental Group. These laboratories engage in collecting information on the climatic influences on the abundance of commercial and recreational fish species; which will enable resource managers and private sector users to anticipate and adjust to changes in resource availability.

Department of Defense (DOD)

The Department of Defense participation in the Global Change Research Program is derived from the Department's extensive research programs in Earth sciences and from the Department's data acquisition programs in support of DOD operations and for other climatic requirements such as systems design and testing. While DOD will not be conducting research to understand global change per se, there are many aspects of DOD activity that will be impacted by global change and those impacts will require DOD study. Additionally, DOD long-term data acquisition activities, particularly oceanographic, will be valuable to focused global change efforts of other agencies. DOD research activities bearing directly on global change issues are dominated by oceanographic research under the sponsorship of the Office of Naval Research, while the long-term oceanographic observations program is conducted under the Office of the Oceanographer of the Navy. Other pertinent, but less extensive, programs are being conducted by the Air Force Geophysics Laboratory, Defense Nuclear Agency and several laboratories within the Army.

Climate and Hydrologic Systems

Contributing ($31.4M)

Research

- *Air/Sea Interaction.* Understanding momentum, moisture and heat exchange between the ocean and the atmosphere is the objective of this research area. Programs in this area seek to develop the methods, theory, and experimentation required to strictly interpret from first principles the interaction between the atmosphere and the ocean, including leads in the ice covered Arctic Ocean.

- *Marine Meteorology.* Totally devoted to understanding weather over the sea, research in this area focuses on the marine atmospheric boundary layer and storms at sea. Key experimental programs ongoing in this area are the ERICA program over the Northwest Atlantic looking at explosive cyclogenesis, a tropical cyclone motion experiment in the Western Pacific, and the Atlantic Stratus Experiment to understand cloud formation and dissipation over the temperate Northeast Atlantic.

- *Small and Mesoscale Physical Oceanography.* The capability to forecast/model the ocean from the fine scale (e.g., turbulence, internal waves) to the mesoscale within a global ocean (e.g., fronts and eddies, basin scale) is the intent of these program areas. A number of ongoing major programs are a part of this effort including SYNOP, Indian Ocean Dynamics, Ocean Subduction, Coordinated Eastern Arctic Experiment, Ocean Waves, and Topographic Interactions. Mesoscale operational models are also being developed for the Gulf Stream, Iceland-Faroes Front, and the Sub-arctic Convergence in the Northeast Pacific. The development of algorithms for merging data from satellites, expendable probes and oceanographic station data is geared toward improving operational forecasting models. The Navy is assisting in the Heard Island Project which is intended to explore the feasibility of monitoring acoustic propagation over global distances, giving direct measurements of the rate of warming of the global ocean.

- *Ocean Remote Sensing.* Fundamental research to understand the interaction of electromagnetic radiation with the surface of the ocean and ice and how subsurface processes modify that signal. This includes synthetic aperture radar, scatterometry, and radiometry.

- *Earth Surface Reflectivity.* Field and laboratory spectral measurements and studies are being conducted in conjunction with instrumented test sites to establish radiation/meteorological data bases and models for given sites (currently temperate and desert locales) as a step towards satellite remote sensing of Earth surface conditions and reflectivity.

• *Global Cloud Distribution and Forecasting*. Research is being conducted to improve the capability of global atmospheric models to predict or specify cloud cover. Results of these efforts by the Air Force Geophysics Laboratory, could be valuable to focused global change research addressing the global radiation balance.

• *Atmospheric Modeling*. Efforts are being made to understand the impact on atmospheric behavior of large dispersions of smoke and dust. Global circulation and mesoscale dynamic models are being improved to incorporate three-dimensional processes and local atmospheric dynamics under perturbing conditions. Efforts are being extended to understand modeling requirements for inclusion of tropospheric gaseous and chemical dynamics.

Observations

• *Long-term observations*. Includes all of the process oriented research efforts presented above. Long-term commitments to each of these research areas and measurement programs are maintained to satisfy DOD needs, and the data archived will be valuable to global change research efforts. Likewise, many of the products of the global observational data sets the Navy collects and maintains to support operational requirements may be valuable in global change assessments. Some of the products from these observational data bases are distributions of sea surface temperature, winds, sea state, thermocline depth, ocean currents, sea ice, cloud cover, storm occurrence, and atmospheric turbulence. Mapping, charting and geodesy surveys conducted by the Navy around the world can contribute to determining shoreline changes, sea level rise, and variations in coastal currents. The Air Force Environmental Technical Applications Center maintains long-term data bases to meet DOD global climatic requirements. Data bases consist of archived global surface and upper air data, global cloud analyses, and global snow cover. Less extensive data from aircraft, satellites, and rocketsondes are also maintained.

• *Environmental Satellite Programs*. This activity includes the Defense Meteorological Satellite Program (DMSP) series of polar-orbiting weather satellites which monitor weather and surface conditions over the globe. DOD controls the DMSP satellites, acquires, processes, and analyzes the satellite data, prepares products, and distributes the products, including some to the Department of Commerce for its use and other civilian customers. The microwave imager on DMSP (SSM/I) measures, among other elements, sea ice extent and concentration. Another sensor on GEOSAT (ALT) measures the relative variations in the level of the sea surface for ocean circulation.

Data Management

• No specific data management costs/centers are maintained. Existing data centers are utilized to archive, preserve and make available all unclassified data. Grantees sponsored to do research in these areas are required to submit, to the appropriate data center, the standard data collected during the course of their grant or contract. Funds to do this are provided as a part of the scientists' normal costs of doing research. Operationally, the Navy gathers global data sets from ships, aircraft, buoys and satellites. Computer algorithms exist for merging these data and making operational forecasts. Collectively, analyses of these data sets are available to the national climatic archival centers. The installation of a Large Scale Computer at the Stennis Space Center within the next two years will provide a unique capability for manipulating massive data sets and providing more detailed oceanographic predictions. It should be noted that the costs associated with routine data acquisition (e.g., weather observations and ocean soundings) are not included in the above contributing cost figure. It is considered, however, that these observational data sets contribute to the data base available for global change research.

Facilities

• While not funded, operated, or maintained for global change assessment, the Navy has 12 specialized oceanographic ships and 3 aircraft capable of making oceanographic measurements. Buoys are deployed in the ocean and on the ice to measure drift, winds, barometric pressure, and sea temperature.

Biogeochemical Dynamics

Contributing ($2.1M)

Research

• *Marine Particle Dynamics.* The study of particle dynamics in the ocean ecosystem leading to the understanding of those processes which are responsible for their abundance, type, and distribution. These particles are responsible for the redistribution of many chemical constituents in the ocean.

• *Marine Photochemistry.* Research on those chemical processes in the ocean accounting for the generation and decomposition of photochemically active compounds.

• *Hydrothermal Vents/Archaebacteria.* Geophysical, geochemical, and biological research at ocean ridges where hydrothermal fluids emanate from the ocean bottom. The focus of the research is to understand the temporal and spatial scales of the phenomenon and the resultant biological, geophysical, and geochemical signatures associated with it.

Long-Term Observations

• Includes all of the process oriented research efforts listed above. Long-term commitments to each of these research areas and measurement programs are maintained to satisfy Departmental needs. The long-term data bases acquired will be of value to global change research efforts.

Data Management

• No specific data management costs/centers are maintained. Existing data centers are utilized to archive, preserve and make available all unclassified data. Grantees sponsored to do research in these areas are required to submit, to the appropriate data center, the standard data collected during the course of their grant or contract.

Facilities

• *Research ship construction and refit.* The Knorr and the Melville research ships are being refitted and a new research vessel (AGOR 23) to be operated by the University of Washington is being built. On the drawing board for FY92 is an additional $45M for a follow on AGOR 24.

Ecological Systems and Dynamics

Contributing ($11.2M)

Research

• *Physical/Biological Ocean Dynamics.* This research thrust couples physical oceanography, ocean optics and biological oceanography in order to understand the mechanisms accounting for biological distributions found in the ocean. This is a broadly supported thrust requiring a multidisciplinary approach as well as regional (e.g. Arctic and Coastal) understanding. Examples of ongoing programs are the Coastal Transition Zone, Coordinated Eastern Arctic Experiment, Topographic Interactions, Marine Light Mixed Layer, BIOSYNOP, and Marine Biosurfaces. Numerical ocean modeling and remote sensing are key enabling science areas and tools for this research.

- *Geophysical/Biological Interactions.* A research area leading to an understanding of benthic community structure from a knowledge of: (1) organisms present, (2) bottom stress and other fluid flow conditions, and (3) benthic biological processes.

Long-Term Observations

- Includes all of the process oriented research efforts listed above. Long-term commitments to each of these research areas and measurement programs are maintained to satisfy Departmental needs. The long-term data bases acquired will be of value to global change research efforts.

Data Management

- No specific data management costs/centers are maintained. Existing data centers are utilized to archive, preserve and make available all unclassified data. Grantees sponsored to do research in these areas are required to submit, to the appropriate data center, the standard data collected during the course of their grant or contract. Funds to do this are provided as a part of the scientists' normal costs of doing research.

Solid Earth Processes

Contributing ($1.0M)

Research

- *Hydrothermal Processes.* Hydrothermal vents play an unknown but potentially important part in our understanding of geophysical and geochemical processes occurring within the ocean. These vents are also well known for their unusual biology. Research in this area is currently focused on geophysical theory related to the formation and stabilization of hydrothermal vent fields.

- *Nearshore Science.* Basic research studying the interaction of the ocean with the shoreline, especially currents and sediment transport inshore of the surf zone. Fundamental understanding of beach erosion processes that will be impacted by rising sea level.

Long-Term Observations

- Includes all of the process oriented research efforts listed above. Long-term commitments to each of these research areas and measurement programs are maintained to satisfy Departmental needs. The long-term data bases acquired will be of value to global change research efforts.

Data Management

- No specific data management costs/centers are maintained. Existing data centers are utilized to archive, preserve and make available all unclassified data. Grantees sponsored to do research in these areas are required to submit, to the appropriate data center, the standard data collected during the course of their grant or contract. Funds to do this are provided as a part of the scientists' normal costs of doing research.

Department of Energy (DOE)

Climate and Hydrologic Systems

Focused ($7.0M)

Research

- *CO_2 and Climate.* Research focuses on the climate system to improve prediction of climate change in response to increase of atmospheric CO_2 and methane. Objectives are to develop/improve models for estimating global and regional climate change due to increasing CO_2/methane, and to evaluate causes of different model results. Emphasis is placed on critical experiments to detect the "early warming" signal, with modification of measurement systems for better definition of quantitative cause and effect relationships. Records are analyzed to detect evidence of climate system response to past and continuing increase of atmospheric CO_2. Climate properties investigated include rate and magnitude of change in parameters such as temperature, precipitation, frequency of extreme events as well as variability of these quantities. Current climate models can not describe rate, distribution and magnitude of regional climate change. To solve this problem it is necessary to understand why models perform as they do, and to improve models so they provide reliable estimates of rate/magnitude of regional climate change. The research addresses questions of climate response to forcings and feedbacks of CO_2 and other radiatively important gases.

Data Management

- *CO_2 and Climate.* Data bases, models and bibliographic information about the climate system are maintained at the Carbon Dioxide Information Analysis Center. Data documentation supports analysis and modeling of climate research. Data quality is reviewed, and exchange of data is fostered among scientists and other users. Communication of CO_2 and climate information is carried out among scientists, policy makers and the interested public.

Biogeochemical Dynamics

Focused ($6.0M)

Research

- *CO_2 and Climate.* Objectives are to determine how global biogeochemical systems influence atmospheric concentration of CO_2 and methane. Includes an inventory of current knowledge of the carbon cycle, and projections of atmospheric CO_2 change. Field investigation and computer modeling provide a quantitative basis for CO_2 exchange among terrestrial, oceanic and atmospheric parts of the carbon system. Natural sources and sinks of CO_2 are evaluated in relation to fossil fuel influences. Relative contribution of physical, biological and energy sources to the changing CO_2 composition of the atmosphere is investigated.

- *In Aerosol Impacts* the objective is to evaluate the role of natural and anthropogenic aerosols in the atmospheric radiative balance and in the modification of clouds. Studies will include field experiments with aircraft and remote sensing as well as numerical modeling of the cloud processes. The global change relevance comes from the possibility that increased aerosol loadings may be cooling the globe.

- *In Precipitation Chemistry* the objective is to relate precipitation chemistry to overall emission patterns and to identify trends in ionic species, organics, and trace metals found in rain. This work currently assists the National Acid Rain Program.

Data Management

• *CO_2 and Climate.* Data bases, models and bibliographic information about the global carbon cycle are maintained at the Carbon Dioxide Information Analysis Center. Data documentation supports models of forcings, feedbacks and prediction of atmospheric CO_2 and methane. Data quality is reviewed, and exchange of data is fostered among scientists and other users. Communication of CO_2 and climate information is carried out among scientists, policy makers and the interested public.

Contributing ($31.1M)

Research

• *Ocean Margin Processes.* The objective is to determine the production and transport of material on the U.S. coastal ocean margins and its interaction with the open ocean. Studies include watermass movements, currents and upwelling dynamics; flux and formation of organic and mineral particles in water column and sediment; biologic productivity including nutrients and lower level food chains. This research is providing information on carbon, nitrogen and phosphorus cycles in coastal systems and the role and volume of injection into the open ocean and exchange with the atmosphere.

• *Fundamental Chemistry.* Provide fundamental knowledge of atmospheric and combustion chemistry processes for reliable modeling of gas/particle emission, including analytical techniques for characterizing trace components of the atmosphere. Understanding of separation techniques is used in emissions reduction technology.

• *Air-Surface Exchange.* Field research based on the turbulent exchange of atmospheric pollutants in and above forest canopies and other terrain features provides estimates of dry deposition. Deposition fluxes are measured from air concentrations and aerosol collection efficiencies by surrogate surface collectors. Field data are used by the National Acid Rain Program. Relationships to global change are the ability of forests to remove atmospheric pollutants and the causes and effects of desertification.

• *Atmospheric Chemistry.* Studies of chemical and microphysical processes in clouds and precipitation explore the interactions of water with natural and anthropogenic pollutants in the atmosphere. Studies of natural and introduced organic species determine their role in modulating the abundance of secondary pollutant species. Experiments on gas-phase reaction kinetics and gas-particle conversions characterize secondary pollutant species. Research involves field studies with ground-based instrumentation networks and airborne sampling platforms as well as laboratory investigations. Diagnostic models are used to analyze field and laboratory results. The cloud and precipitation studies support the National Acid Rain Program. The principal relationship to global change is the influence of primary and secondary pollutants on long range air and precipitation quality. Also relevant is the ability of storm systems to redistribute pollution on a global basis.

• *Biological Mechanisms.* In supportive research Energy Biosciences emphasizes the understanding of how biological activities of plants and microorganisms transform key components, such as CO_2, CH_4, SO_2, NH_4 and of the carbon, nitrogen, and sulfur cycles. Comprehension of the mechanisms by which these transformations occur and the requisite conditions for the changes is the information being sought.

• *Subsurface Transport.* The objective is to determine the geochemical processes of transport and transformation of natural and introduced substances in the subsurface and their movement through unsaturated and groundwater systems. Studies include molecular level soil/chemical interactions, distribution and metabolism of microbial communities, and hydrologic modeling.

Long-Term Observations

• *Air-Surface Exchange.* Routine measurements of dry deposition at several key sites across the U.S. are currently used for the validation of the acid rain models.

Data Management

• *Atmospheric Chemistry.* The data bases acquired during the various intensive field efforts are currently used by the National Acid Rain Program for the validation of the source-receptor models. Data are computer-archived, quality assured and available to the scientific community upon request.

Ecological Systems and Dynamics.

Focused ($4.2M)

Research

• *CO_2 and Climate.* Experimental research and modeling provides information about effects of CO_2 and climate with vegetation and ecological systems. Focus is to determine primary effects from new experimental data and models, and to validate predicted changes. System-level properties are examined for CO_2 and climate effects include basic primary productivity; altered structure, function and composition of ecosystems; plant-animal-microbial relationships; and water balance/hydrology. The research addresses questions of ecosystem and large-scale biotic response to changes in the Earth's atmospheric and terrestrial systems, and provides fundamental knowledge on processes and mechanisms.

• *Theory in Biological/Physical Systems.* The objective is to strengthen and expand a theoretical underpinning for complex global systems thereby providing better definition for modeling and experimental design. A central core for development of integrating theory, interactive with data collection and analyses from local to large-scale processes is being emphasized to obtain better theoretical definition for processes of global and regional dynamics.

Data Management

• *CO_2 and Climate.* Data bases, models, and bibliographic information about vegetation and ecological systems are maintained at the Carbon Dioxide Information Analysis Center. Data documentation supports models of ecosystem response and prediction of ecosystem change. Data quality is reviewed, and exchange of data is fostered among scientists and other users. Communication of CO_2 and climate information is carried out among scientists, policy makers and the interested public.

Contributing ($8.3M)

Research

• *Ecosystem Research.* Effects of multiple impacts on critical ecosystems and resiliency of the ecosystems are determined. Changes in energy, water usage and nutrients are quantified in ecosystems impacted by both natural and human induced stresses to detect early signs of ecological change; research includes holistic multidisciplinary studies on regional watersheds and landscapes ranging from climate sensitive arctic tundra and semiarid sites to humid, and subtropical regions which are primarily located on the large DOE National Environmental Research Parks. These studies over four decades provide the data for elucidation of regional patterns to biosphere response of environmental change.

Long-Term Observations

• *Ecosystem Research.* For over 30 years basic environmental data continues to be collected at five DOE National Environmental Research Parks providing a baseline for determining fluctuations and trends in naturally and artificially stressed ecosystems. Computer networks are being established between the DOE National Environmental Research Parks and Arctic sites for exchange and intercomparison of data sets. Data sets are being developed for compatibility and use with the Federal Interagency Data Management Group.

Earth System History

Contributing ($0.4M)

Research

• *Geosciences.* Studies of possible impacts of bolides on Earth's biota, including possible correlation of variations in concentrations of rare Earth elements and mass extinctions that have long been used as geological time markers.

Long-Term Observations

• *Geosciences.* Measurements of iridium and other elements across the C-T and other boundaries using samples from throughout the world.

Human Interactions

Focused ($2.0)

Research

• *CO_2 and Climate.* Analysis provides estimates of future CO_2 emissions. Objective is to understand technologies for producing/transforming and using energy, and the technologies for recovering/sequestering CO_2 emissions, including relationships between technology, economics, ecology, geology and other factors. Scope includes scientific, technological and socio-economic data needed to project future energy use trends/patterns and associated emissions of 'greenhouse' gases. Potential improvement of energy output per unit of CO_2 emission is determined for conventional and advanced fossil fuel technologies. Expected reduction of CO_2 emission from different energy (e.g., efficiency profiles, alternative technology mixes) and environmental control technologies are assessed.

Data Management

• *CO_2 and Climate.* Data bases, models and bibliographic information about energy systems are maintained at the Carbon Dioxide Information Center. Data quality is reviewed, and exchange of data is fostered among scientists and other users.

Solid Earth Processes.

Contributing ($6.7M)

Research

• *Geosciences.* Examine geophysics and geochemistry of crustal rock, fluid systems, volatile emissions and transport processes. The field program, including Continental Scientific Drilling investigates rock deformation, crustal response and seismicity, and develops the knowledge base for remote sensing of reservoir structures. Results provide a quantitative understanding for predicting energy-related Earth processes.

Long-Term Observations

• *Geosciences.* Acquisition of seismic data at locations of special interest for understanding crustal processes.

Data Management

• *Geosciences.* Includes data sets concerning federal drilling activities, brine properties, and measurements resulting from DOE managed Continental Scientific Drilling Projects.

Solar Influences

Focused ($1.0M)

Research

• *Geosciences.* Studies of solar-terrestrial-atmospheric interaction help understand one of the factors that may initiate or perpetuate global change, namely: solar variations and their coupling to the Earth and near-Earth environment. Studies include: energy transport in near-Earth space plasma; the solar wind-magnetospheric interaction; energetic particle phenomena from a few keV to many MeV; radiation from space and astrophysical plasmas; magnetic field annihilation in the magnetosphere and its applications to the Earth and near-Earth environment; solar physics and the dynamics of the sun; and the employment of long-term changes in the shape and diameter of the Sun as an indirect diagnostic of changes in the solar constant.

Long-Term Observations

• *Geosciences.* Long-term measurements of solar insolation, energy transfer, space plasma and magnetospheric substorms and their impact on U.S. energy systems.

Data Management

• *Geosciences.* Collection and management of data sets from long-term outer atmospheric observations.

Department of the Interior (DOI)

Climate and Hydrologic Systems

Focused ($1.8M)

Research

• *Snow and Ice.* Remote sensing studies of snow and ice dynamics as a means of gaining understanding of: ice/atmosphere interactions, glacier mass-balance and sea ice extent as indicators of climate. (United States Geological Survey)

• *Evapotranspiration Processes.* Studies of the rate of evapotranspiration from areas of natural vegetation as a function of atmospheric conditions, vegetation and land surface conditions, and moisture availability. Advances in these studies are needed for estimation of the water balance (runoff and ground water recharge) under various climatic scenarios. (United States Geological Survey)

• *Modeling.* Development of more realistic treatment of hydrologic processes in atmospheric models; collaboration with climate modeling community, such as the Geophysical Fluid Dynamics Laboratory (GFDL) and the National Center for Atmospheric Research (NCAR), to develop capability to improve the characterization of hydrologic conditions and processes which are the primary driving forces behind energy and moisture fluxes at the land/atmosphere interface. The purpose of this work is to improve the accuracy of atmospheric models used to predict climate change and the resulting water budgets for the earth's surface. (United States Geological Survey)

• *Hydroclimatology.* Study of the relationship between atmospheric circulation and hydrologic conditions (primarily streamflow). These studies should provide improved capabilities to predict the water-resources implications (in terms of water supplies, and the probabilities of droughts, and floods) more directly from atmospheric circulation model outputs. (United States Geological Survey)

• *Integrated River Basin Studies.* Study of the impacts of various climate change scenarios (changes in temperatures and precipitation amounts) on entire river basins. This involves estimation of changes in evapotranspiration, runoff, ground water recharge, water use, sea level, and the resulting changes in water quality (especially salinity) in estuaries and coastal aquifers. In 1989 such research is underway in the Delaware River Basin; it is aimed at development of appropriate tools for hydroclimatic impact assessment. (United States Geological Survey)

• *Glacier Monitoring.* Research effort satellite and aerial remote sensing of the world's glaciers, with emphasis on high latitudes, for evidence of glacier response to global warming. Melting of glacier ice will be the primary contributor to the projected rise in sea level. (United States Geological Survey)

Contributing ($90.6M)

Research

• *Spatial Data Collection and Analysis Techniques.* Development of advanced tools and techniques (e.g. geographic information systems, remote sensing technology, and computer modeling for spatial Earth-science data base integration) contributes to linking climate change to Earth surface changes. (United States Geological Survey)

• *Hydrologic Processes.* Development and application of methods of measurement and assessment of water resources at the local, regional, and national scales. This includes work on streamflow, ground water movement in the saturated and unsaturated zones, estuary hydrodynamics, and associated studies of geomorphology and sediment transport. (United States Geological Survey)

• *Geographic Information System (GIS) Research.* Development of GIS and other spatial data analysis tools and techniques to support research involving climate and hydrologic systems. This includes techniques for geographic analysis and modeling of space- and time-dependent phenomena using large mutidisciplinary earth-science data sets. (United States Geological Survey)

• *Long-Range Transport Modeling.* Develop and apply Eulerian models to make estimates of pollutant concentrations on a regional scale. Model estimates include sulfur dioxide, sulfate, and ozone concentrations based on approximations of long-range transport and dispersion, dry and wet deposition, and chemical transformation. (National Park Service)

• *Physical Oceanography.* Program consists of studies of the circulation patterns within the Outer Continental Shelf and the mechanisms creating those patterns. An understanding of the general dynamics allows for the support of diagnostic and predictive modeling efforts. (Minerals Management Service)

• *"Greenhouse" Warming Effect.* Studies with emphasis on addressing the effects of climatic change on water supplies and water use and appropriate coping strategies for managing the water resources of the West for various scenarios include: (a) preparing inventories of watershed sensitivity to climatic change, (b) research studies to bridge the gap of uncertainty between general circulation model output and hydrologic models. (Bureau of Reclamation)

• *Changing Water Requirements.* Analytical review of changing water needs and development of improved methods for calculating water demands, including accommodation of climate change. (Bureau of Reclamation)

• *Surface and Groundwater Characterization.* The program objectives include evaluating factors affecting surface runoff, erosion and stream flow; groundwater levels and characteristics. Information is being gathered that will be helpful in understanding likely effects of changing climate on hydrology and water quality. (Bureau of Land Management)

Long-Term Observations

• *National Map and Digital Data Production.* Maps and digital data provide basic land surface information for studies of climate and hydrologic systems. (United States Geological Survey)

• *Water Resources Data.* Operation of a national network of data collection stations (and associated data base) where basic information on water resources is gathered. These data include streamflow and river, lake, or reservoir stage determinations at about 12,500 sites, and measurements of ground-water levels or pumpage at about 34,000 locations. Although these data have not been collected for this specific purpose, they are a key element of the analysis of the hydrologic aspects of global change. (United States Geological Survey)

• *Fire Weather/Climate Studies.* 200 Remote Automatic Weather Stations (RAWS) spaced on 75 mile grid continuously monitor real time weather in the western United States. A lightning detection system is operated in conjunction with weather stations. Monitoring data are archived in a data management system. These stations are compiling weather/climate data from remote areas of the western U.S. where climate data has previously not been available. This information is particularly valuable in the arid and semi-arid areas of the west where the large spatial and temporal variability of temperature and precipitation already presents a significant challenge to natural resource management. Regional influences of global climate change may be better interpreted with use of these stations. (Bureau of Land Management)

• *Weather and Tide Stations.* In compliance with the Compacts of Free Association, Territorial and International Affairs (TIA) reimburses the National Weather Service (NWS) for operating and maintaining weather stations and tide stations in the Republic of the Marshall Islands, the Federated

States of Micronesia, and Palaie (Trust Territory of the Pacific Islands). The weather stations provide forecasts and storm warnings. The tide stations are part of the Tsunami Warning System. The NWS cooperates with the Navy. (Territorial and International Affairs)

• *Fine Particle Monitoring*. Obtains aerosol mass, ion, organic carbon, elemental carbon, and trace elements in two size ranges using multi-stage cyclone particulate samplers at 34 parks. The program includes quality assurance, data reduction, and data base management. (National Park Service)

Data Management

• *Information and Data Services*. Includes acquiring, archiving, managing, and integrating graphic, digital, and remotely sensed data which contribute to studies of climate and hydrologic systems. (United States Geological Survey)

Biogeochemical Dynamics

Focused ($0.2M)

Research

• *Carbon Cycle Research.* Development of improved understanding of the role of carbon in hydrologic and geologic processes (precipitation and dissolution of carbonates in marine, estuarine, and terrestrial environments) and the fate, transport, and biogeochemical role of natural organic compounds in a variety of environments. (United States Geological Survey)

Contributing ($1.2M)

Research

• *Gas Content of Evaporite Formations.* Techniques developed to measure gas content of evaporite formations (salt, potash, and trona) for methane. In addition, a new method for determining methane gas content of coal will be validated. (Bureau of Mines)

Long-Term Observation

• *Air Quality.* Studies primarily monitor dispersion of airborne contaminants (CO, SOx, NOx, VOC, and particulates) at Outer Continental Shelf (OCS) platforms and an array of offshore buoys. Data is collected to develop a data base from which trends could be determined. (Minerals Management Service)

Ecological Systems and Dynamics

Contributing ($36.6M)

Research

• *Plant Growth Rate.* Studies of the growth rate of bottom hardwood forest species were initiated (1) to identify relationships between seasonal tree growth and major environmental factors including subsurface water level, (2) to analyze historical tree growth from three lowland sites in southern Illinois for influences by flooding and other environmental factors identified above, (3) to compare historical growth of several bottom and oaks in terms of their response to environmental conditions and (4) to determine the historical changes in the diversity of wetland communities. (Office of Surface Mining, Reclamation & Enforcement)

• *Rangeland Ecosystems.* Research in the northern Great Basin to understand better the effects of fire on rangeland ecosystems. Studies of plant varieties and their resistance to wildfire and tolerance to increasing aridity and thermal stress possibly occurring as a result of climate change. (Bureau of Land Management & Bureau of Indian Affairs)

• *Integrated Ecological Research in Small Watersheds.* Pilot research program in remote "natural" watersheds to evaluate natural and anthropogenic influences on ecosystem processes, including biogeochemical cycles. (National Park Service)

• *Research on Species Populations.* Field and laboratory research to determine environmental tolerances and habitat requirements for selected plant and animal species. The program focuses substantially on species and their ecological importance, sensitivity to change, or potential ability to take advantage of ecological disturbance. In addition to studies of native species, major emphasis is on the ecology of non-native invasive species, insect pests and disease organisms, and experimental evaluation of chemical, cultural, mechanical, and biological methods for control. (National Park Service)

• *Man and the Biosphere Program.* Interdisciplinary research relating to global change is one of several priorities of the U.S. Man and the Biosphere Program will facilitate use of the international network of biosphere reserves as "biosphere observatories" for comparative interdisciplinary studies of global change. In FY 89, USMAB co-funded initiation of an integrated cooperative program including multimedia background pollutant monitoring, ecological studies, and watershed research involving paired watershed sites in the U.S. and the U.S.S.R. (tundra-taiga ecotone, northern hardwood forests, mountain broad-leafed forests). Other proposals under MAB review relating to global change focus on wildfire risk assessment, dynamics of ecotones, establishment of circumpolar observatories, subsistence uses, environmental archaeology, synthesis of historical data, and a case study of the Everglades. (National Park Service)

• *Wilderness Management Studies.* Inventory of wilderness and wilderness study area characteristics, baseline monitoring of sensitive indicators. Baseline monitoring of these remote and unique areas will provide a basis for studying the long-term trends of these ecosystems with minimal influence from mans' development. Approximately 25 million acres in 860 separate tracts have been identified as wilderness study areas. (Bureau of Land Management)

• *Biology.* These studies describe the distribution and interactions of benthic and pelagic communities and populations. The studies describe the biological aspects of fisheries, birds, turtles and non-endangered species, as well as the dynamics of population changes. Monitoring is long-term and reflects population and community response to changing climatic and marine conditions. (Minerals Management Service)

• *GIS Applications in Landscape Analysis.* Analysis of distributional patterns of species and ecological communities in relation to climatological, hydrological, edaphic, land use, and other landscape variables is being conducted routinely in many NPS areas using several GIS software packages. Notable applications involve modeling of ecosystem interactions at Everglades National Park, and development of potential habitat maps for spotted owl, bald eagle, grizzly bear,and peregrine falcon at North Cascades National Park. (National Park Service)

• *Wetland Loss in the Mississippi Delta and Louisiana.* Study to document the rate and location of loss of coastal wetlands in Louisiana, especially the Mississippi Delta. Although this loss has been the result of many factors, including relative sea level rise, EPA has used these loss rates to project nationwide losses. FWS is now looking at (1) changes in the rate of loss, (2) attempting to quantify the contributions to the loss rate from the various courses (channelization and subsequent erosion; subsidence from oil and gas production; loss of sediments from construction of levees; sea level rise). (Fish & Wildlife Service)

• *Assessment of Biological Diversity on Preserves.* Development of protocols and methodologies which use species richness and biological diversity to identify and map habitat for protection and management of wildlife, including endangered species. Although designed to be used as a tool for acquisition and management of preserved areas, it will provide overlay maps of specific terrestrial habitats and biological diversity and species richness indices. These would be useful both in planning for response to climate change, and as baselines to assess the impact of climate change. (Fish & Wildlife Service)

• *Species Status and Habitat Research.* Studies to understand the distribution and habitat requirements of endangered species. Because they live on the edge of survival and are often highly dependent on specific habitat types, even subtle changes in habitat (or climate) may cause a noticeable impact on their abundance and distribution. For this reason, endangered species have often been suggested as excellent indicators of climate change. (Fish & Wildlife Service)

• *Vegetation Classification and Analysis.* Development of site specific ecological classifications using photo interpretation and digital image analysis for incorporation into park geographic information systems, including limited R&D relating to techniques and applications. The baseline classifications may be useful in characterizing changes in potentially sensitive ecological communities (e.g. disjunct communities; ecotonal areas such as timberlines), or changes in the distribution of dominant species. The NPS has technical capability in assessing vegetation trends using historical and contemporary photography and satellite imagery. (National Park Service)

• *Baseline Monitoring of Ecological Communities.* Development of basic information on the structure, ecological relationships, species composition, spatial distribution, and phenology of ecological communities in NPS units. Data sets from permanent plots in many parks document ecological succession following natural and anthropogenic disturbance, as well as trends in mature natural communities. Baseline information on ecological conditions and trends in NPS areas will contribute to process and effects studies of ecosystems likely to be sensitive to global change, including: Relict communities, high latitude forest and tundra communities, coral reef and kelp communities, coastal barrier communities, ecotonal communities, and altitudinal gradient communities. (National Park Service)

• *Baseline Monitoring of Species Populations.* Development of basic information on long-term trends in the structure, dynamics, genetics, and habitat associations of animal and plant populations utilizing NPS areas for all or part of their life cycles. Emphasis is on population parameters that are easily measured, sensitive to stress, and useful in forecasting future population trends. Involves monitoring of species potentially sensitive to global change, including endemic, rare, threatened, or endangered species; species with strict habitat requirements; potential opportunistic species such as insect pests, disease organisms (including ticks and other vectors of human disease), and invasive nonnative species; as well as species important in regulating ecosystem processes which, if affected by global change, would significantly influence species trophic and/or community relationships in park ecosystems. (National Park Service)

• *Pilot Inventory and Monitoring Program.* Development of guidelines for systematic inventory and monitoring of park resources. The program includes assessment of the status of existing inventory and monitoring activities, and design and implementation of pilot projects in selected NPS areas to provide models for long-term monitoring of a wide range of park ecosystems. (National Park Service)

• *National Wetlands Inventory and Mapping.* National responsibility for the inventory and mapping of wetlands of the United States. This effort, currently scheduled for completion in FY 1998 for the lower 48 coterminous states, has provided baseline maps and data of wetland acreage, distribution, and type. It not only provides mapped, site-specific information, but statistically significant data on wetland losses (acreage), changes (types), and trends. As wetlands are likely to be one of the early indicators of global climate change effects, the baseline inventory data as well as the status and trends inventory will be useful to document actual impacts. (Fish & Wildlife Service)

• *Migratory Bird Program.* Responsibilities for management of migratory birds, especially waterfowl, require that we annually census waterfowl populations and certain habitats of importance to their survival. These censuses are international in scope, extending into Canada and accomplished in part under the Migratory Bird Treaty Act. The census information represents 30 years of data relating to abundance and distribution, and can serve as a baseline for future change. (Fish & Wildlife Service)

• *Fish Stock Assessments.* Stock assessments or status surveys of fish species and populations in different watersheds are conducted on a continuing basis. Data for some species and watersheds, e.g., salmonids on the Columbia and Snake Rivers, striped bass in Eastern (Gulf and Atlantic) rivers, or Great Lakes fisheries, are more regular than others; such data are collected annually and used for management of fishery resources, fish hatcheries, and management of water resources (flows, dams, etc.). These surveys would serve as baselines for assessing climate change effects on fishery resources in the face of change. (Fish & Wildlife Service)

• *Rangeland Studies.* Ecological site baseline studies and inventory, vegetation monitoring and trend. Ecological site inventories are conducted to determine baseline data on large areas (4 million acres in FY 89). Vegetation monitoring studies include assessment of plant community indicators such as frequency of species, density, ground cover, and key climate parameters related to vegetative growth i.e. precipitation, temperature. A fundamental objective of rangeland monitoring in the western U.S. is to distinguish between the activities of man and the influence of climate over time in the rangeland ecosystem. (Bureau of Land Management & Bureau of Indian Affairs)

• *Wildlife, Fish, and Threatened and Endangered Species.* Wildlife habitat monitoring and trends studies, threatened and endangered species inventory and monitoring. The streams, lakes, reservoirs, and rivers on public lands provide key habitat for many species of cold and warm water fish. BLM administers 13,000 miles of anadromous fish streams and 20,000 miles of stream habitats for resident game fish. Climatic influences on surface and groundwater flow is critical to the future of these riparian areas. Monitoring of threatened and endangered species (T/E) provides a very sensitive measure of mans activities. Studies to implement recovery of certain T/E species will provide insight into the capability of various ecosystems to adapt and survive future management actions. (Bureau of Land Management)

• *Endangered Species.* The objectives of the endangered species studies are to obtain data pertaining to the distribution and interrelations of species listed as "endangered" or "threatened" and to determine potential effects of OCS oil spills, on these species. Animal tagging and monitoring is an important feature of this program. (Minerals Management Service)

Data Management

• *Natural Resource Data Management.* Automated data systems and natural resource data bases including soils, vegetation, ecological condition, wilderness, air and water quality, and climate information. (Bureau of Land Management)

• *NPFlora and NPFauna Database.* The National Park Service manages NPFlora, an automated checklist and information base on vascular plants documented from 148 NPS areas. Where UTM coordinates exist, locations of known species occurrences are integrated into park GIS data bases. Most of the more than 75,000 records for vascular plants are not precisely geo-referenced. A comparable Service-wide data base, NPFauna, is being developed for vertebrate fauna in cooperation with The Nature Conservancy. These data bases have potential applications in recording and summarizing changes in species occurrence that may be related to global change. (National Park Service)

• *Natural resource collections.* Natural resource collections from National Park System areas are sources of information for correlating evidences of global change. In particular, biological, environmental, paleoecological and archaeological collections can provide useful evidence of long-term trends. A pilot collections management plan being developed for Great Smoky Mountains

National Park will consider the role of natural resource collections in integrated ecological monitoring and research in biosphere reserves. The plan will include particular requirements for documentation, preservation, and use of types of collections relevant to research on global change in the Southern Appalachians. (National Park Service)

Earth System History

Focused ($1.3M)

Research

• *Paleoclimatology and Paleohydrology.* Research directed at establishing the rate, frequencies, and magnitudes of climate change through analysis of the geologic record (including terrestrial and marine cores and related botanical and geochemical records) and provides information on the prehistoric natural variability of climate during the last thousands to millions of years. This information on past climates is providing data to improve and test general circulation models (GCMs) that are being used to predict future climates. The following topics of research will be emphasized:

Paleohydrology: Reconstruction of hydrologic and climatic conditions in the Great Basin during the past 1 million years with emphasis on the past 25,000 years.

Terrestrial Coring: Mechanized core drilling to obtain long, continuous records of terrestrial climate conditions at a variety of key geographic locations.

Pliocene Climates: Synoptic reconstruction of global climates and environments during warm intervals of early Pliocene as analog for greenhouse warming in the next century.

Ice Core Glaciology: Development of new capability in the USGS to study paleoclimate data preserved in glacier ice cores from Greenland, Antarctica, and other ice caps.

Paleoecology: Application of paleontological data and methods to reconstruction of past climates, and the impacts of past changes on ecosystems.

Isotopic Analysis: Application of isotopic methods to provide chronological measure of climate-sensitive isotopic variations through time.

Desertification/Desert Processes: Expansion of existing USGS research on desertification and other climate-sensitive surficial processes. Includes monitoring of climate and erosion/depositional processes in arid regions.

Marine Paleoclimates: Research aimed at obtaining high quality records of paleooceanographic and paleoclimatic history preserved in marine sediment cores.

Permafrost Studies: Monitoring of permafrost temperatures and heat-flow profiles in Alaska and other high latitude sites in both polar regions for evidence of global warming; studies of changes in the distribution and depth of permafrost.

Glacial History: Reconstruction of past changes in the extent of glacier ice during the past 2 million years. (United States Geological Survey)

Contributing ($0.6M)

Research

• *Geochronology.* Provides the essential time scales to the geologic record that permit reconstruction of the history of climatic changes and other events. (United States Geological Survey)

• *Dendrochronology.* Studies establish chronological tree-ring data files from the present time to as far back as datable specimens, living and dead, will allow. On-going NPS research focuses on developing fire histories for NPS areas including information on the seasonality of fire in western parks, histories of drought events in midwestern parks, mapping the frequency and areal extent of tsunamis in Alaskan coastal areas, and correlating climatic changes and pre-European social disruptions in the western United States. (National Park Service)

• *Paleoecology.* Analysis of sediment cores from lakes, ponds, salt marshes, barrier islands and tidal flats to correlate chemical and biotic changes in sediments with past changes in climate, sea level, vegetation and anthropogenic influences. (National Park Service)

• *Environmental Archaeology.* Studies develop correlative evidence of past climatic and ecological conditions from cultural artifacts and biological materials from archaeological excavations. (National Park Service)

Human Interactions

Focused ($1.5M)

Research

• *Land Surface and Geographic Processes.* Research is conducted on the interactions between human activities and natural processes by inventorying vegetation, land-use changes; and determining environmental impacts. This research involves integrating remotely sensed data and Earth-science data for applications such as vegetation monitoring as an indicator of cultural impacts. (United States Geological Survey)

• *Coastal Processes.* Research effort aimed at assessing the geologic consequences of climate change and resultant impact on human activities on our coastlines. Global climate warming is expected to accelerate the rise in sea level, and many nations will be faced with difficult decisions on whether to attempt to protect or to abandon the coast. Through a better understanding of coastal processes and the sediment budget of the coastal zone associated with a rising sea level an improvement in our ability to predict future erosion and rapidity of coastal retreat will be possible. (United States Geological Survey)

Contributing ($68.1M)

Research

• *Landslide Hazards.* Identifies and maps high-risk populated areas on the basis of conditions preceding historic landslides, morphological evidence of past failure, and analysis of geologic setting having landslide potential. (United States Geological Survey)

• *Water Quality.* This research is focused on the fate and transport of chemical constituents in rivers, ground water, and estuaries. These studies include analyses of the role of river discharge, land use, effluent discharges, atmospheric deposition, geologic and soil materials, and various aquatic and terrestrial organisms, erosion and sediment transport and deposition. (United States Geological Survey)

• *Geographic Information System (GIS) Research.* Development of GIS and other spatial data analysis tools and techniques to support research on the interface between human activities and natural processes. This includes techniques for geographic analysis and modeling of space- and time-dependent phenomena using large multidisciplinary earth-science data sets. (United States Geological Survey)

• *Shoreline Recession Associated with Developed Shorelines.* The research establishes rates of retreat, mechanisms of retreat, and separates causes of retreat (sea level rise, storms, and altered rates of sediment supply due to dredging, coastal stabilization, and other human activities), then assesses degree of threat to human communities within park boundaries, NPS developments, and NPS natural areas, as appropriate. The program includes frequent updating of an extensive network of shoreline surveys. (National Park Service)

• *Resource Ethnography.* Ethnographic studies of resource uses by natives and other small-scale societies provide empirical benchmarks for monitoring effects of global change. This year, a study of changing subsistence adaptations, and subsistence mapping, is being completed at Lake Clark. Similar studies are programmed for future initiation in northwest Alaska. (National Park Service)

• *Cultural Resource Studies.* Inventory and scientific evaluation of archaeological and paleontological resources evidencing prehistoric human adaptation to the environment. Archaeological and paleontological inventories and evaluations can provide insight into mans' ability to adapt to the climatic influences of prehistoric environments and evidence of the vegetative adaptations that may have been cultured by man. About 125,000 archaeological and historic properties have been recorded representing the tangible remains of thousands of years of human adaptation to the environment. (Bureau of Land Management)

Long-Term Observations

• *National Map and Digital Data Production.* Maps and digital data provide basic land surface information for studies of human activities and natural processes. (United States Geological Survey)

• *Water Quality Networks.* The USGS operates over 12,000 water-quality monitoring stations. Among these are the only two national networks for water quality monitoring: NASQAN (about 500 stations) that measure the status and trends and estimated fluxes of many constituents from the major river basins of the Nation; and the Hydrologic Benchmark Network (about 50 stations) in highly pristine locations which are thus very sensitive to atmospheric driven changes (precipitation amounts and precipitation chemistry) as opposed to being sensitive to terrestrial impacts of man. The USGS also coordinates the National Trends Network for measuring atmospheric deposition of major ions at about 150 stations nationwide. (United States Geological Survey)

Data Management

• *Information and Data Services.* Includes acquiring, archiving, managing, and integrating graphic, digital, and remotely sensed data which contribute to studies of human interactions and natural processes. (United States Geological Survey)

Solid Earth Processes

Focused ($0.5M)

Research

• *Coastal Processes.* Drawing on the present USGS Coastal Erosion Program, the program would be expanded nationally beyond present studies of barrier erosion in Louisiana to include the densely populated portions of the barrier islands of the Mid- Atlantic and southeast coasts, and the Alaskan coast where, particularly in the Arctic, erosion rate of 10 m or more per year have been recorded. The research will be conducted in close cooperation with the appropriate State Geological Surveys and University coastal researchers. The emphasis will be on coastal processes and changes by sea level rise and the potential impact of mitigation measures. (United States Geological Survey)

• *Volcano Processes.* Research effort aimed at achieving a better understanding of explosive and effusive volcanic eruptions. Of particular importance to global climate change is the volume of tephra (volcanic ash, CO_2, SO_2, and other gases which are injected into the atmosphere during such events. Cooperation will eventually be undertaken with climate modelers to better link geological observations to global circulation models. (United States Geological Survey)

Contributing ($11.8M)

Research

• *Dynamics of Coastal Systems.* The program continues 25 years of NPS research in coastal geomorphology, applied research on beach/dune dynamics, estuarine processes, sediment transport by waves and currents, and backbarrier sedimentation, and barrier island studies at national seashores and other coastal parks. The research includes projections of future landscape change based on long-term observations to establish variability and long-term trends in coastal processes. A proposal for a major coastal and marine park initiative beginning in FY 90, including climate change impact studies, is now being completed. (National Park Service)

• *Volcanic Eruptions.* Program to investigate the volume, distribution, and chemical and physical characteristics of erupted materials; work with NOAA and other Federal agencies to relate volcanic products and processes to change in climate and sensitive environments. (United States Geological Survey)

• *Landslide Hazards.* Landslides occur most frequently during and after periods of heavy precipitation and, therefore, are related to a change to wetter climates, studies of historic landslides will provide additional information on this empirical correlation. (United States Geological Survey)

• *Offshore Geologic Survey.* Geologic Long-Range Inclined Asdic (GLORIA) side-scan sonar images permit the identification and geographic location of large numbers of previously unknown submarine volcanos and areally massive lava flows on the sea floor that, when active, can inject gases and other eruptive products into the ocean and atmosphere, thereby causing short- or long-term changes in climate. Of particular interest are studies of volcanic processes taking place on or adjacent to the crest of active spreading ridges, intraplate volcanos, and volcanic arcs. (United States Geological Survey)

• *Geographic Information System (GIS) Research.* Development of GIS and other spatial data analysis tools and techniques to support research involving solid earth processes. This includes techniques for geographic analysis and modeling of space- and time-dependent phenomena using large multidisciplinary earth-science data sets. (United States Geological Survey)

Long-Term Observations

• *Earthquake Data and Information Service.* The USGS operates a Global Seismographic Network. The Network is currently being expanded and modernized in a cooperative venture in the National Science Foundation's Global Change and Continental Lithosphere Programs. Improved information on seismicity helps to define small-scale lithospheric plate deformation that can change apparent sea level, be used in forecasting great earthquakes, and perhaps, indirectly, influence volcanic activity. (United States Geological Survey)

• *Volcano Hazards.* Three volcano observatories (the Hawaiian, Cascades, and Alaska Volcano Observatories) are maintained to gather data associated with effusive and explosive volcanic activity. Considerable effort is made to improve the methodology of predicting volcanic eruptions. Predictions of major eruptions can impact whole countries and might, in the future, themselves be factors in global change; in addition, a prediction of a great eruption would enable researchers in global change to prepare for measurements in impact. (United States Geological Survey)

• *Offshore Geologic Surveys.* The USGS operates, in cooperation with NOAA, a GLORIA side-scan sonar system to acquire images of the sea floor within the Exclusive Economic Zone of the United States. (United States Geological Survey)

• *National Map and Digital Data Production.* Maps and digital data provide basic land surface information for studies of solid earth processes. (United States Geological Survey)

Data Management

• *Information and Data Services.* Includes acquiring, archiving, managing, and integrating graphic, digital, and remotely sensed data which contribute to studies of solid earth processes. (United States Geological Survey)

Solar Influences

Contributing ($2.0M)

Long-Term Observations

• *Geomagnetism.* Monitor changes in global geomagnetism through a network of 11 observatories and by field surveys. The monitoring of real-time magnetic indices provides basic information on changes in the Earth's magnetic field, and its atmosphere. (United States Geological Survey)

Environmental Protection Agency (EPA)

Climate and Hydrologic Systems

Focused ($0.7M)

Research

• *Regional Climatic Scenario Production.* To provide physically plausible and analytically coherent descriptions of regionalized climate conditions under "greenhouse" conditions. Assessment of potential effects of "greenhouse" effects requires that regional climatic conditions be determined. Currently, even the most highly-resolved General Circulation Models cannot provide realistic regional resolution, although they will be used to the maximum extent feasible. To circumvent this restriction, this scenario research uses historical or proxy data (such as from tree rings or oxygen isotope ratios) and regional models, where available, to develop detailed regional climate descriptors, or scenarios. This research will, in the near-term, provide scenarios of plausible climatic conditions under various greenhouse conditions, allowing analyses of sensitivity of regional-scale ecological processes to be assessed. The scenarios will provide detailed conditions to a variety of research to support an integrated basis for analysis of interlocked systems, such as hydrology and freshwater fisheries.

• *Air Quality.* To provide evidence of changing air quality due to changing global and regional climates and, in particular, the effect of increased UV irradiance on ozone formation and air quality. Cities presently in compliance with the NAAQS for ozone may not be in compliance in the future if UV irradiance increases due to the depletion of stratospheric ozone, or if other climate related changes occur in tropospheric chemical reactivity. Synergistic reactions among precursors, UV irradiance, and ozone are important parts of this research.

Contributing ($13.9M)

Research

• *Regional Acid Deposition Model.* To model the transport and transformation of emissions. The modeling of the contribution of one region to the deposition in another requires that credible and efficient quantification of complex atmospheric processes be described in an appropriate model. This research includes field evaluation of the performance of the model, leading to source attribution for regional deposition.

• *Regional Oxidant Model.* To model the chemistry and transport of oxidants within the boundary layer. Oxidants in the troposphere are an increasingly important aspect of air pollution. This research is developing and testing a regional and mesoscale model of oxidant formation, transport and destruction within several layers of the boundary layer.

• *Urban Air Pollution.* To model concentrations of urban air pollutants on time scales ranging from minutes to decades. This research supports the development and evaluation of atmospheric diffusion of criteria pollutants in many differing situations, such as the effect of highways, plume entrapment in building wakes in urban regions, and various source configurations, such as individual industrial plants or urban area sources. The problems addressed by this research include air quality attainment, the impact of carbon monoxide, and short-term peaks of concentration in urban environments.

Biogeochemical Dynamics

Focused ($0.8M)

Research

• *Radiatively Important Trace Gases.* To investigate, quantify, and model the emissions of important RITG's, with early emphasis on methane and nitrous oxide. Methane is emitted by several processes, both natural and man-made. Among them are important anthropogenic sources, including rice paddies, and anaerobic, natural wetlands. Nitrous oxide is emitted by man-made combustion, as well as biogenic nitrogen cycles, including emissions from fertilizer application. The emission factors for these two RITG's will be investigated, including the effect of increased levels of UV radiation on some of the processes. Feedback processes in ecosystems are an important part of this effort. In addition, a coordinated activity with NOAA will study the effect of UV-B radiation on components of important atmosphere/hydrosphere biogeochemical cycles, including trace-gas precursors (such as VOC's) of tropospheric ozone. The development of reliable emissions factors for combustion sources of nitrous oxide is an important near-term product of this research, as is a technological assessment of potential control methods.

• *Atmospheric Chemistry Kinetics and Modeling.* To quantify and model the kinetics of tropospheric trace gases in atmospheric conditions. Chemical kinetics of reactive RITG's play an important part in modeling atmospheric chemistry, and therefore understanding the relations among sources, sinks, transport, transformation, and reactivity. This research emphasizes development of multiple-gas interaction kinetics, for input to air quality models on both regional and global scales.

• *Pollution Interrelationship Research.* Interrelationship of other air pollution problems and global atmospheric change. This includes coordination and joint research with other air programs. In addition, global climate change and stratospheric ozone depletion will be included in analyses done on future projections of both tropospheric and stratospheric air quality and planning.

• *Ozone Depletion Trends.* Analysis of changes in stratospheric concentrations and ozone depletion trends. The EPA will be involved in analysis of trends of concentrations of various atmospheric compounds and their effects on future atmospheric conditions.

• *Emissions Sources.* Analysis of point and non-point source emissions and their impacts on global climate change. Such emission areas include livestock, agriculture and man- made sources. Emissions from these sources play an important role in global climate change and analyses will be conducted to better understand the dynamics involved in change and the possibilities for limiting or eliminating these emissions.

Contributing ($3.7M)

Research

• *Regional Acidic Emissions.* To develop detailed emission data bases of acid deposition precursors, principally SO_2, NO_x, and VOC's, from all U.S. continental sources, or source aggregations. Current efforts are focusing on developing an emissions data base for 1990, and on maintaining analytical models for producing projections of future emissions under a variety of assumed scenario conditions.

Ecological Systems and Dynamics

Focused ($7.4M)

Research

• *Regional Climate Change Effects.* To investigate the effect of changing climate on ecosystem processes. Includes interactions with air quality scenarios. Sensitivity of biotic region boundaries to climatic conditions, and potential alterations under differing scenarios of climate change. Climatic interactions with ecosystems determine where specific biotic populations and communities exist. Selected examination of historic and paleoecological records of ecological responses to changing climate. Over the longer term of research, feedbacks between biogenic responses to changing climate (including effects of alterations in land use) and biogenic emission rates of RITG's will be investigated and quantified.

• *Terrestrial Ecosystems.* To investigate and quantify the effects of increased UV-B irradiance at the Earth's surface. Determination of (1) biochemical, physiological, anatomical, morphological and phenological changes, (2) mechanistic bases for response, (3) range of species and cultivar variation in sensitivity, and (4) ability to mitigate potential impact.

• *Plant Competition.* To investigate and quantify the effects of increased UV-B irradiance at the Earth's surface. To determine the mechanistic basis for the differential sensitivity to UV-B radiation between species within a natural or agro-ecosystem, competition studies will be carried out within highly structured field plots.

• *Forested Ecosystem.* To investigate and quantify the effects of increased UV-B irradiance at the Earth's surface. Loblolly pine seedlings initially have served as the model for forest species to determine the response of individuals within a forested ecosystem to increased levels of UV-B irradiance.

• *Marine Fisheries.* To investigate and quantify the effects of increased UV-B irradiance at the Earth's surface. To determine the impact of UV-B radiation on components of the marine ecosystem, including those species that serve as a human food source, both micro- and mesocosm studies are used. The results of these experiments will serve as input variables for various fisheries models.

Long-Term Observations

• *UV-B Irradiance.* To drive the baseline, control exposure for the field experiments at the various EPA research sites, and also to serve as the core of a developing UV spectral irradiance monitoring network.

Data Management

• *Quality Assurance.* Due to the potential regulatory implications of EPA's research results, a comprehensive, peer-reviewed QA/QC and data management program for effects of UV irradiation is required.

Contributing ($52.4M)

Research

• *Air Quality Interactions with Ecosystem Processes.* To investigate, quantify, and model the impact of tropospheric air quality on ecosystem productivity and succession. The deleterious effects of tropospheric ozone are of increasing interest, with implications that have aroused concern for several other ecosystems, including high elevations. This research addresses damage mechanisms, air chemistry during transport and transformation and modeling of biotic response. A near-term product of this research is a Regional Oxidant Model (ROM) that interfaces with biotic response models now being constructed.

• *Water Quality Effects on Ecosystem Processes.* To investigate, quantify, and model biotic response to alterations in water quality. The importance of water quality for maintenance of ecosystem function is the focus of this research. The investigations include a wide range of important ecosystems, including wetlands, the Great Lakes, coastal waters, and with respect to hazards, deep oceanic waste disposal. A strong influence in this research is the development of risk characterization and risk assessments for aquatic ecosystems, often in conjunction with biotic-response models.

• *Pesticides Transport and Ecosystem-Level Effects.* To trace pesticide movement through ecosystems, model their transformations and effects, and assess ecosystem-level risk associated with them. The complex ecological interactions that pesticides engender are the focus of this research, with field work in coastal waters. Field data collection is included in ecosystem-level models to support integrated assessments.

• *Toxic Substances Research.* To investigate ecosystem- level effects of toxic substances, with emphasis on aquatic environments. This research uses microcosm-based methods to investigate the hazards associated with toxic substances. The results support ecosystem-level assessments of effects, with attention to quantifying ecological change (Question D). Integrated assessments of ecological risk is a major emphasis.

• *Acid Deposition Effects Research.* To identify, quantify, and model the ecological effects of acidic materials deposited on, or transported through, ecosystems. This large research effort has provided significant advancement to the understanding of acidic materials in ecosystems, both terrestrial and aquatic. Field studies of forest response to airborne pollutants and of forest ecosystem response to artificially acidified watersheds are providing valuable inputs to biotic response models. Aquatic ecosystems have been investigated for both short-term effects related to hydrologic events and longer-term responses to ecological change. Ecosystems contain many parallel or linked processes that affect movement of chemicals and water in and through soils, thus significantly affecting growth and productivity. This research is evaluating the success that ecosystem-scale models of contrasting resolution possess with respect to predicting ecological responses. A near-term output will be a description of the success of these models. The National Trends Network provides nationwide coverage (with widely-spaced samplers) of both wet and dry deposition. The Mountain Cloud Chemistry Program provides more specialized data regarding fog chemistry, usually at high elevations. Status and trends data reflecting surface-water chemistry is an important part of this research.

• *Environmental Monitoring and Assessment Program (EMAP).* EPA is initiating EMAP to monitor the status and trends of the nation's ecosystems and to evaluate the effectiveness of Agency policies aimed at protecting the ecological resources occurring in these ecosystems. The intent of this program is to establish a long-term data base on ecosystem condition using a standardized set of indicators and sampling design. The ecosystems being evaluated include forests, freshwater wetlands, surface waters, agroecosystems and the near coastal environment, including wetlands, estuaries, and the Great Lakes. EMAP will use existing data to formulate the study design and it will seek to integrate its activities with existing federal, regional and state monitoring programs.

Data Management

• *Data Base Management.* To provide archival and retrieval services for long-term monitoring. The data from long-term observations are routinely archived in large data- base repositories.

Human Interactions

Focused ($18.5M)

Research

• *Research/Policy Analysis (Impact Assessment/Adaptive Policies).* To improve understanding of the impacts of climate change on society and to assess potential adaptive policy options. Development of climate data sets, analyses of national and international impacts on water resources, agriculture, natural ecosystems and man-made systems; identification of guidance, when warranted for public/private officials.

• *Research/Policy Analysis (Stabilizing Strategies).* To improve understanding of possible future global emissions; to assess technological options and costs for limiting emissions; to identify institutional, economic, and cultural barriers; to identify country-specific options; and to assess international strategies. Pay-off: policy options for senior government officials involved in international discussions.

• *Human Health.* To provide critical information on the capacity of UV-B radiation to modulate the immune system. To determine the adverse health effects, a study will evaluate UV-B-induced changes in the immune system in human subjects and the influence of skin pigmentation. In addition, a study coordinated with the Department of Health and Human Services will determine the effects of UV-B exposure on the incidence, severity and recurrence of a spectrum of infectious diseases in experimental models.

• *Support of the Montreal Protocol.* Reassessments of effects and technology studies completed in support of the Montreal Protocol. As part of the U.S. obligations under the Montreal Protocol, The EPA will be an active participant in a series of assessments based on continuing scientific and technological advances. These assessments will be completed in 1989 and will be used for the scheduled renegotiations on the Protocol.

• *Alternative Technologies and Strategies.* Research on alternative technologies and strategies for regulated chemicals. This involves research and investigation on alternative manufacturing techniques and chemical compounds to replace those that have been regulated by the Montreal Protocol. In addition, the EPA will be examining various control strategies and options and will conduct analyses to weigh the benefits of controls and substitutes.

• *Implementation of Regulations.* Implementation of the U.S. domestic regulations of CFC's and halons under the Montreal Protocol. This involves the development and enforcement of the domestic regulation and insurance of compliance of U.S. industry with the Protocol.

• *Domestic Regulatory Actions.* Assessment of the need for further domestic regulatory actions to implement the Montreal Protocol. The EPA issued an ANPRM on the same day as the final regulations in which the Agency proposed additional regulatory activities, related auctions or fees, or direct regulations in the event that industry does not respond quickly enough to reduce their use of regulated chemicals. The EPA will be conducting research and analyses toward a decision.

• *International Assessments.* Participation in the international assessments of Protocol stringency. This includes scientific research on the causes and effects of ozone modification and future atmospheric projections.

National Aeronautics and Space Administration (NASA)

Climate and Hydrologic Systems

Focused ($4.3M)

Research

• *Earth Observing System (Eos).* Development of technology to measure from integrated polar-orbiting platforms all aspects of the physical climate system, including: Earth radiation budget; surface temperature (land & ocean); winds; atmospheric temperature and water vapor; atmospheric aerosols; cloud properties and cover; precipitation rate; ocean circulation and waves; sea ice extent, character, and motion; snow and ice extent and character; volume and mass balance of terrestrial ice sheets; surface soil moisture and wetlands extent.

• *Hydrologic Cycle in Atmosphere-Surface Interactions.* To study the spatial and temporal patterns of the components of hydrologic and climatic processes that control the forcings and the fluxes between the Earth's surface and its atmosphere. Utilization of remote sensing in studying and assessing the coupled interactions of the Earth surface with the atmosphere through hydrologic processes. New proposals have recently been approved for research as part of NASA's Earth Science and Applications Interdisciplinary Research Program. The goal is improved understanding of the role of hydrologic components in the climate system at regional and global scales.

• *Detection of Changes and Identification of Forcings Due to the "Greenhouse Effect" in the Climate System.* To search for evidence of enhanced "greenhouse" warming and for identification of the most probable forcings in the climate system. Examination of available long-term global data records for the patterns of change expected in various climatological variables associated with "greenhouse" warming. New proposals have recently been approved for research as part of NASA's Earth Science and Applications Interdisciplinary Research Program. The goal is improved ability to detect the signature of global climatic change due to the "greenhouse" effect.

Contributing ($178.3M)

Research

• *Remote Sensing Techniques.* Advances in our knowledge of climate and hydrologic cycle physical processes are dependent on the availability of reliable datasets to test and refine climate models. The primary source of these global data is satellite based remote sensing. NASA supports the development of improved and advanced techniques for remotely sensing important atmospheric parameters (e.g., passive and active temperature sounding, precipitation, radiation fluxes, evaporation). This includes supporting laboratory and field measurements, modeling, and data analysis.

• *Global and Regional Climate Studies.* NASA sponsors research on the detection and characterization of processes associated with the "greenhouse" forcing of climate change. This includes studies of the global climate record as well as case studies of drought/flood using conventional and satellite observations in models, diagnostically and prognostically.

• *Cloud- Radiation Processes.* To better understand the role of cloud feedback in climate change, NASA supports satellite, airborne, and surface-based observations of cloud cover and radiative properties, data analysis and modeling. This research is organized primarily within the structure of the First ISCCP Regional Experiment (FIRE), an interagency (NASA, NSF, DOD, and NOAA) coordinated research program in support of the World Climate Research Program (WCRP). The results of FIRE are being applied to improving the parameterization of cloud processes in climate models.

• *Global-Scale Weather Process Studies.* Use of satellite-derived data and modeling to develop a better understanding of the processes which maintain the atmospheric general circulation and which result in the variability commonly called "weather".

• *Regional Studies of Hydrologic Cycle Components.* NASA sponsors and coordinates major field experiments to understand land surface/vegetation/atmosphere interactions. An example is the First International Satellite Land Surface Climatology Project Field Experiment (FIFE). A concentrated effort was made to understand important surface/atmosphere interactions such as evapotranspiration.

• *Hydrologic Cycle in Land-Atmosphere Interaction.* To support investigations of the states and dynamics of the regional and global storages and fluxes of the land components of the Earth's hydrologic cycle. The research is based on a combination of classical approaches and airborne and space-based remote sensing techniques. This effort will provide needed information for understanding the land-atmosphere interaction at the regional and global scales under the global change initiative.

• *Biosphere Contributions to Atmosphere Circulation.* The conduct of multidisciplinary field experiments to investigate the role of the biosphere in regional and global atmospheric circulation. The approach is based on the concurrent measurement of surface and atmosphere parameters during certain states or events with the aid of conventional and remote sensing techniques. This effort will help to understand the processes that contribute to short-term fluctuations and long-term trends in regional and global environments.

• *General Circulation Models (GCM).* This effort is intended to provide a tool for studying the interaction of Earth's land and ocean surface with the atmosphere through simulation and with the aid of models that properly describe the contributing land surface processes at the regional and global scales. Deriving input parameters for these models and/or estimating the rate/state of the processes from remotely sensed data is the ultimate goal. This will provide a non-destructive means of global monitoring of such processes with the aid of remote sensing and will lead to more accurate prediction of climate change and its effects.

• *Ocean Circulation & Air-Sea Interaction.* To determine the circulation, heat content, and horizontal heat flux of the global oceans, how they are influenced by the atmosphere, and how they in turn influence climate. Spaceborne scatterometer and altimeter observations, in conjunction with appropriate *in-situ* measurements – especially those made via NSF's World Ocean Circulation Experiment (WOCE) and NOAA/NSF's Tropical Ocean Global Atmosphere (TOGA) program, will be used to estimate the surface wind stress and topography of the global oceans, from which atmospheric forcing and ocean current response can be estimated. Altimeter observations from the Navy's Geosat satellite are being used to estimate seasonal changes in the topography associated with the oceanic mesoscale circulation. The ultimate benefit is to assess the role of the oceans in the redistribution of heat from low to high latitudes.

• *Sea Ice & Ice Sheets.* To determine characteristics of polar ice cover, how the atmosphere and ocean influence variations in these characteristics, and how the variations in turn influence climate. Spaceborne synthetic aperture radar (SAR), radar altimeter, and microwave radiometer observations of the polar regions, in conjunction with appropriate *in situ* measurements, are used to characterize polar ice cover. Both DMSP/SSMI-derived sea-ice cover and and Geosat/altimeter-derived altimeter ice-sheet topography estimates are being compiled. The ultimate benefit is to assess the role of sea-ice cover and ice-sheet topography in changing climate.

• *Ocean Topography Experiment (TOPEX).* To implement a dedicated altimeter mission, joint with the French Space Agency (CNES), called TOPEX/POSEIDON, to observe the surface topography of the global oceans with sufficient accuracy to enable a determination of the mean and variable circulation, as well as the tides. Development is underway with a launch date in early 1992. TOPEX, in concert with WOCE and TOGA, should enable the first comprehensive determination of the circulation of the global oceans.

• *NASA Scatterometer (NSCAT).* To develop a scatterometer sensor, initially to fly on the Navy's NROSS satellite but now proposed for the Japanese ADEOS mission, to observe the surface roughness of the global oceans with sufficient accuracy to enable a determination of the surface wind stress field. Although the funding level has been recently reduced in view of no formal flight agreement, development for FY 89/90 is continuing at a level in order to permit NSCAT to meet the ADEOS launch date of early 1995. NSCAT on ADEOS will observe more than 90% of the global ocean surface every two days and will enable the first comprehensive determination of the global surface wind stress field, a prime driving force for the oceanic circulation.

• *Aircraft Operations* :

  • *Land Surface Climatology.* Airborne sensors to provide an intermediate scale of observation to that of ground and satellite sensors for measurement of surface temperature, moisture conditions, vegetation index, and for estimation of mass and energy exchanges between the land surface and the atmosphere.

  • *Regional Land Surface Hydrology.* Airborne observations of soil surface water content, of surface water flows and drainage patterns, and of snow extent, depth, and its equivalent water content (PBMR, ESTAR) are used to study the storages and fluxes of water within the land components of the hydrologic cycle.

  • *Atmospheric Parameters.* Airborne measurements of atmospheric parameters like aerosol backscatter, rain rate etc. are important for designing appropriate satellite-borne instruments and in validating remotely-sensed data.

Long-Term Observations

• *Earth Radiation Budget Experiment (ERBE).* The objective of ERBE is to acquire a long-term record of the global and regional radiative fluxes at the top of the Earth's atmosphere to improve our understanding of storage and transport of energy in the climate system. Current research emphasis is on the processes associated with cloud forcing and feedback.

• *Global Hydrologic Processes.* NASA utilizes the long-term, multi-frequency passive microwave observations from the DMSP series of satellites. That data will provide an archive of the climatology of global precipitation, atmospheric moisture, oceanic evaporation, ocean wind stress, snow cover extent and soil moisture.

• *Regional and Global Surface Hydrology.* The objective is to provide long-term records of near-surface soil water content, and surface snow depth and its water equivalent for studying their role in regional and global hydrologic processes. The approach is based on a combination of surface-based networks of observations and airborne and space-based measurements of emitted electromagnetic energy from the surface. This research should help improve the parameterization of hydrologic and general circulation models.

• *Mission Operations and Data Analysis (MO&DA).* Provides for the extended operations, data processing, validation, and data analysis of spaceborne missions which observe the Earth radiation budget, land surface climatology and hydrology, and atmospheric water vapor.

Data Management

• *NASA Climate Data System (NCDS).* To improve the processing and archiving of global and regional climate data sets and to simplify their accessibility by the scientific community, NASA has developed the NCDS in conjunction with the National Space Science Data Center. The data made available through the NCDS include key Earth radiation budget parameters such as albedo, solar radiation, and thermal radiation as well as sea ice coverage, clouds, and aerosols.

• *International Satellite Cloud Climatology Project (ISCCP).* The capabilities of current climate models to address such contemporary climate problems as the greenhouse warming issue is limited largely by the unavailability of a reliable cloud climatological data set. The production of these needed global data sets of cloud coverage and radiative properties (e.g., cloud type, opacity, temperature, and height) is supported by NASA within the framework of the World Climate Research Program (WCRP). The ISCCP involves the collection and processing of the cloud images acquired by the international network of operational meteorological satellites. The ISCCP data sets are archived on the NCDS and at NOAA's National Climatic Data Center.

• *DMSP/SSMI Data Archival.* To improve the scientific community's capability to access and work with spaceborne observations being collected by the DMSP/SSMI microwave radiometer. Global SSMI water vapor, precipitation, wind-speed and sea-ice cover products are being produced and archived. A prototype sea-ice archive is being developed for the National Snow and Ice Data Center (NSIDC) in Boulder, CO; an archive for wind-speed and related products is being set up at JPL in Pasadena, CA, helping lay the basis for the archival of data from the flight of NSCAT (noted above).

• *Geosat Data Archival.* To improve the community's capability to access and work with Geosat/altimeter-derived ice-sheet topography of Greenland and certain Antarctic coastal areas. Topography based on both Seasat (1978) and Geosat (1985-present) has been estimated for Greenland; the inherent noise in the signal precludes at this time distinguishing any significant change in the topography over the past ten years, however, the Geosat data suggest that the southern high-elevation parts of the Greenland ice-sheet are thickening by perhaps 10 cm per year . These data are being archived at NSIDC. Geosat ocean products will be archived at JPL, helping lay the basis for the archival of data from the TOPEX mission (noted above).

• *Pilot Land Data System (PLDS).* To enhance the access and availability of airborne, space-based, and ground-based land related data sets by the scientific community, NASA has sponsored development of PLDS. The data made available through PLDS include an inventory and catalog of both conventional point measurements as well as remotely sensed image data. PLDS has a significant role to play in providing access to regional and global data sets by the scientific community studying the Earth as a system and any change in its climate.

• *International Satellite Land Surface Climatology Project (ISCLCP).* This project was formed to study the extent to which satellite data can be used to study the energy and mass balance exchanges between the Earth's land surface and the atmosphere. The First ISLSCP Field Project (FIFE) was conducted to acquire simultaneously and process ground-based, airborne, and space-based observations of surface energy and mass balance components of hydrological and climatic processes at the regional scale. Analysis of these data should help provide the needed information for studying the role of the biosphere in regional climate change, as well as development and testing of algorithms for deriving the rate and magnitude of land surface processes from remotely sensed data. The FIFE information system provides the basis for conducting such research.

• *Alaska SAR Facility* To implement a capability to receive, process, archive, and distribute synthetic aperture radar observations of polar ice cover from European (launch in late 1990), Japanese (early 1992), and Canadian (1994) satellites. Formal agreements have been consumated with the European Space Agency and the Japanese Space Development Agency regarding receipt of data from their spacecraft; an agreement is pending with the Canadians. Not only will this capability permit detailed observations of the Arctic sea-ice cover, it will also enable the preparation of the first radar-derived map of the Antarctic continent, revealing characteristics of its ice sheets.

Biogeochemical Dynamics

Focused ($3.0M)

Research

• *Earth Observing System (Eos).* Development of technology to measure from integrated polar-orbiting platforms all aspects of the biogeochemical cycles, including: Ocean primary productivity, atmospheric constituents and energy inputs, land surface characteristics. Eos Advanced Technology Development (ATD) is currently part of the Environmental Observations Payload and Instrument Development, and as a program it is scheduled for a New Start in FY91. The goals of the program will be to provide observing and information systems to study the global change processes, from an Earth System Science viewpoint. There will be four polar-orbiting platforms, two provided by NASA, one by ESA, and one by Japan. The instrument complement will include NASA research facility instruments and principal investigator instruments selected by a NASA Announcement of Opportunity process. The Data and Information System is an integral part of the program, and it will have to handle about a terabit of data per day.

Contributing ($147.0M)

Research

• *Trace Gas Fluxes from Ecosystems and their Fate in the Troposphere.* To develop regional- to continental-scale understanding of sources, sinks, fluxes, and fates of trace gases and of their global significance. Use of remote-sensing and *in situ* methods to measure the emissions of radiatively and photochemically important trace gases from ecosystems and their chemistry and transport in the troposphere; modeling of biogeochemical cycling processes in ecosystems. Emphasis to date has been on measurements of seasonal and annual fluxes of methane from terrestrial and aquatic ecosystems. This research will lead to an improved understanding of changes in the atmospheric concentrations of trace gases that can perturb the Earth's chemical composition and climate.

• *Tropospheric Chemical Processes.* To determine the processes that control tropospheric chemical species concentrations and distributions. Aircraft and ground-based measurements of fluxes and meteorological mixing processes combined with satellite measurements (where available). Extensive field measurement campaigns in the tropical Atlantic, the Amazonian rainforest, and the Alaskan tundra. Provides quantitative large-scale data as critical input to models of the impact of changing atmospheric chemistry on climate.

• *Stratospheric Processes.* To develop an understanding of the chemical and physical processes which control the composition and structure of the Earth's upper atmosphere and its susceptibility to change (with particular emphasis on stratospheric ozone and climate). *In situ* and remote measurements of chemical species (source and trace gases), atmospheric dynamics, and climatology; laboratory measurements of important reaction kinetic, photochemical, and spectroscopic parameters; multidimensional models of the coupling of chemistry, radiation, and dynamics together with the analysis of satellite and field measurement data. Continued balloon and aircraft field measurements programs including the Airborne Arctic Stratosphere Expedition; continued laboratory experimental efforts with accelerated research on heterogeneous chemistry; modeling assessment of the global impact of the Antarctic ozone hole. Provides for improved predictions of changes in stratospheric ozone in response to human activity.

• *Upper Atmospheric Research Satellite (UARS).* To obtain the first global-scale data base on chemistry, dynamics, and energy input to the upper atmosphere and the coupling among them. Dedicated fully-instrumented satellite system to be launched in 1991. Instrument development and testing; ground data system procurement and installation; development of planned ground-truth and correlative measurements campaigns. Improved understanding and prediction of stratospheric ozone and climate change.

• *Ecosystem Processes.* To estimate vegetation canopy composition and structure, to infer nutrient cycling rates, and to drive models of ecosystem productivity and biogeochemical cycling. Satellite and experimental airborne sensors are used to measure or estimate (in visible and infrared wavelengths) leaf area index, chlorophyll density, canopy photosynthetic potential, net primary productivity, and forest canopy lignin and nitrogen concentrations. This information is validated through comparison with complementary ground-based measurements and by extension to other types of ecosystems. This canopy information then is related to nutrient cycling processes and rates and also is used as input to ecosystem process models. This research will lead to a better understanding of the controls that terrestrial ecosystems exert on biogeochemical cycling, of ecosystems' storages and major fluxes of nutrients, and of the spatial and temporal variability of biogeochemical cycling processes on the terrestrial landscape.

• *Ocean Productivity.* To determine primary productivity of the oceans, how it is influenced by the oceanic circulation and the atmosphere, and how it in turn influences the marine food chain, the rate of CO_2 uptake by the oceans, and climate. Spaceborne ocean color observations, in conjunction with appropriate *in situ* measurements--especially those made via NSF's Global Ocean Flux Study (GOFS), will be used to estimate the primary productivity and the associated phytoplankton biomass. Preparations are underway to support the GOFS North Atlantic Experiment with airborne ocean color observations. The ultimate benefit is to assess the role of the oceans as a sink for atmospheric CO_2.

• *Sea-WiFS Implementation.* To provide a capability for follow-on, but improved over the Coastal Zone Color Scanner (CZCS), ocean color observations. This will be done via the initiation of a joint venture with EOSAT regarding Sea-WiFS (compact wide field sensor) for flight on Landsat-6 in 1991. An agreement in principle with EOSAT is near finalization.

• *Payload Development.* To develop, test, and evaluate Earth remote sensing instruments and system for the measurement of atmospheric constituents, energy input, and land surface characteristics.

• *Aircraft operations.* Testbeds for future satellite instruments to measure atmospheric chemical composition and land surface characteristics, as well as vehicles for special field projects such as:

  • *Atmospheric processes.* Global Tropospheric Experiments and Polar Ozone Expeditions (Arctic and Antarctic).

  • *Canopy Chemistry.* High spectral resolution reflectance data from the Airborne Visible-Infrared Imaging Spectrometer (AVIRIS) to estimate vegetation canopy lignin, nitrogen, and chlorophyll concentrations.

  • *Areal Extent of Wetlands.* Remotely sensed estimates, using aircraft optical and radar sensors, of the areal extent and seasonal inundation dynamics of wetlands for use in extrapolating point measurements of trace gas fluxes to larger scales.

Long-Term Observations

• *Tropospheric and Stratospheric Monitoring.* To determine the rate of change in the atmospheric concentrations of anthropogenic and naturally occurring tropospheric source gases; to develop a long-term data base on the chemical composition of the stratosphere and the ability to detect and interpret changes in important constituents. Measurements of important source gas concentrations at selected locations around the globe via the Global Atmospheric Gases Experiment (GAGE); and the development of a network of stations for the Detection of Stratospheric Change through the development, testing, and deployment of various ground-based remote-sensing instruments.

• *Vegetation Process Monitoring*. Advanced Very High Resolution Radiometer (AVHRR) data, both vegetation index and thermal data, are being compiled to understand global patterns of productivity, fire, and land cover change. The vegetation index calculated using red and infrared wavelength radiances is used to estimate an ecosystem's leaf area index or its potential photosynthetic capacity at a point in time and its net primary productivity when integrated over the growing season. A long-term data set of monthly averaged, global vegetation index data is analyzed to examine seasonal, annual and interannual patterns of productivity. The results of this research will greatly improve our understanding of terrestrial ecosystem productivity and of how productivity varies over time in response to changes in climate and human activities. AVHRR thermal data are being used to estimate the frequency and extent of fires related to deforestation in the tropics; this research should yield some understanding of the role of fire in biogeochemical cycling in tropical ecosystems.

• *Satellite Measurements and Data Analysis* . Measurements and data analysis of a number of important environmental parameters from existing satellite instrumentation including atmospheric ozone (Total Ozone Mapping Spectrometer (TOMS) and Stratospheric Aerosol and GAS experiment (SAGE II)); nitrogen dioxide, water vapor, and stratospheric aerosols (SAGE II); and a large number of atmospheric constituents utilizing the ATMOS flown on shuttle. Analysis of data from Shuttle Imaging Radar (SIR-B) mission.

Data Management

• *CZCS Data Archival*. To improve the scientific community's capability to access and work with ocean color observations made during the lifetime (1978-86) of the Coastal Zone Color Scanner (CZCS). Global data from the CZCS mission is being reprocessed, now that there is an improved understanding of the degradation in sensor gain; data products are then archived and made ready for community use. Eighteen months of data have actually been reprocessed and will shortly be distributed by Goddard Space Flight Center (GSFC) on optical disks to a number of university sites. The CZCS archival activities at GSFC in Greenbelt, MD will help lay the basis for the archival of data from the flight of Sea-WiFS (noted below).

• *Information Systems*. Funding for continued operation of scientific computing resources and data archives in support of all NASA Earth Science and Application activities, including study of biogeochemical cycles.

Ecological Systems and Dynamics

Focused ($4.3M)

Research

• *Earth Observing System (Eos)*. Development of technology to measure from integrated polar-orbiting platforms quantities important to land and ocean ecological systems, including: Surface temperature, radiation, albedo, surface humidity, primary productivity, leaf area, vegetation type, soil moisture, and evapotranspiration.

Contributing ($13.8M)

Research

• *Landscape Dynamics*. To document and understand the spatial distribution, areal extent, and changes in pattern of major land cover types on the Earth's surface. Satellite imagery at several differing spatial scales is being used for land cover mapping and inventory, to document vegetation patterns on the terrestrial landscape, and to analyze change in these patterns over time. Global vegetation index (AVHRR) and surface moisture (SMMR) data sets collected since 1981 are being used to study large-scale changes in vegetation patterns over time. Landsat and SPOT data are being used for fine-scale studies of local to regional vegetation patterns. These studies will yield insights in large-scale processes influencing vegetation patterns and will provide information on vegetation-climate interactions. In addition, these results will be useful in a wide variety of studies which require information on the spatial extent of land cover types and temporal variation in vegetation.

• *Ecosystem Structure and Composition.* The basic biophysical and biochemical determinants of reflected, emitted, and backscattered radiation from vegetation canopies are being investigated in order to understand and interpret remotely sensed data from terrestrial ecosystems. Controlled observations of electromagnetic radiation interactions with plants are made in the laboratory, in the field, and from aircraft in order to understand the contributions of various ecosystem components to the radiances received by a satellite. Models are used to simulate these interactions and to predict the responses of vegetation under known conditions. Results will improve our ability to utilize remotely sensed information from terrestrial ecosystems precisely and quantitatively.

• *Ecosystem Modeling.* Realistic, mechanistic, simulation models of ecosystem processes (including production, decomposition, nutrient cycling, evapotranspiration, and succession) which can be driven with remotely sensed inputs are being developed to yield insight into the function of terrestrial ecosystems and to predict their response to changes in the environment. Existing ecosystem process models are being modified to accept primarily remotely sensed inputs, and new models are being developed which exploit remotely sensed information or data which is potentially sensible remotely. An increasing emphasis is on the development of nested, hierachical models and models which can be linked to provide for feedbacks from one model to another and which can simulate interactions between ecosystem components and between ecosystems and climate or the hydrological cycle. These models should greatly improve our understanding of the interactions among ecosystems, the atmosphere, and the hydrosphere. They will also permit us to generate predictions about ecosystem response to change and ecosystem controls through feedbacks on climate and the hydrologic cycle.

• *Payload development.* To develop, test, and evaluate Earth-viewing remote sensing instruments and systems to obtain data for land remote sensing research, including terrestrial ecosystems.

• *Aircraft Operations* :

  • *Landscape Pattern.* Use of both active and passive airborne sensors covering all useful portions of the electromagnetic spectrum for measuring the spatial distribution and areal extent of terrestrial ecosystems on local to regional scales.

  • *Vegetation Structure.* Radar, laser, and bidirectional passive optical observations of ecosystems to measure or infer such structural properties as canopy height, branch and leaf orientation or distribution, stand density, leaf area index, and, in some cases, canopy species composition.

  • *Energy Balance of Vegetated Surfaces.* Airborne thermal sensors (TIMS) for measuring surface temperature to use in calculations of evapotranspiration; bidirectional reflectance measurements (using ASAS) to more accurately estimate the albedo of vegetated surfaces.

Long-Term Observations

• *Global Vegetation Patterns.* To understand global vegetation patterns and their change over time. Monthly averaged, global Advanced Very High Resolution Radiometer (AVHRR) vegetation index data and Scanning Multichannel Microwave Radiometer (SMMR) polarization difference data (related to surface moisture) for the period 1981-present are being processed and compiled. These data will constitute a long-term, coarse-scale data base which can be analyzed for change over time and change in response to specific environmental perturbations.

• *Regional Observations.* Fine spatial scale Landsat Multispectral Scanner System (MSS) and Thematic Mapper (TM) imagery and SPOT imagery for selected, climatically sensitive regions of the globe have been preserved and archived. These data are being housed at a NASA facility and all non-commercial data can be made available to interested scientists. Studies of fine-scale change in land cover patterns for selected regions of the Earth's surface are being conducted and these changes are being related to changes in climate and human activities in the areas involved. These data will constitute a long-term, fine-scale data base which can be analyzed for change over time and change in response to specific environmental perturbations.

Data Management

• *Global Vegetation Index.* Monthly averaged, global AVHRR vegetation index data and SMMR polarization difference data for the periods 1981-present and 1979-1987 respectively are being preserved and archived. These data bases will be updated and made available to the scientific community through the Pilot Land Data System (PLDS) in future years. These data will constitute a long-term, coarse-scale data base which can be analyzed for change over time and change in response to specific environmental perturbations.

• *Landsat Browse Facility.* NASA-owned, historic Landsat MSS and TM data have been archived and are being made available through the NASA Landsat Browse Facility. Information about commercial Landsat data (that data acquired after the Land Remote Sensing Commercialization Act was enacted) can be made available through this facility, but the data itself must be ordered through Eosat. An electronic data base of all holdings has been implemented. These data will constitute a long-term, fine-scale data base for selected regions of the Earth which can be analyzed for change over time and change in response to specific environmental perturbations.

Earth System History

Contributing ($4.5M)

Research

• *Evolution of Continents.* The objective of this research is to investigate the history and evolution of the continents from early formation and deformation through accretionary, depositional, tectonic, and deformational processes that are currently active. The approach is based on a combination of geological field and laboratory observations and remote sensing techniques. This research improves our understanding of solid Earth processes from early crustal formation through to present activity.

• *Quaternary Processes.* This research is directed toward understanding of geomorphic, volcanic, and paleoclimatological processes and their role in the evolution of land surfaces over the past million years. A combination of field, laboratory, and remote-sensing observations of geologic formations, land surface processes, and rates of processes is employed. Studies of land surfaces and composition contribute to understanding tectonic processes, soil formation and erosion, weathering and modification of geological surfaces, and the development of drainage networks. Studies of volcanism and global volcanic activity contribute to assessment of potential natural hazards, to global heat flux analyses, and to the understanding of atmospheric chemistry changes attributable to volcanic volatiles. Studies of past climatic change prior to human influence provide a yardstick of natural variation and rates of change, contributing to the assessment of human present and future impact and the anticipation of future rates of change.

• *Technique Development.* A combination of ground-based, and air and space-borne passive and active remotely sensed data acquired at different regions of the electromagnetic spectrum are used to develop a wide range of techniques to study geological materials, features and phenomena. These techniques are particularly valuable for studying regional features and active phenomena in remote areas of the globe.

- *Aircraft Operation:*

  - *Structure, and Composition.* Use of multi-sensor (UV, visible, near and shortwave infrared, thermal infrared, and microwave) airborne observations for structural, lithologic, and compositional mapping of the Earth's surface to provide information on the geologic processes responsible for the evolution of the continents.

  - *Surface Geomorphology.* Use of both active and passive airborne sensors covering all useful portions of the electromagnetic spectrum for measuring surface roughness and geomorphic patterns which can be used to infer the recent geologic, volcanic, and climatic processes that shaped them. Use of laser altimeter for detailed profiling of geographical features.

Human Interactions

Contributing ($0.6M)

Research

- *Acid Deposition Effects.* To develop a better understanding of the affects of acidic deposition and air pollution on ecosystems. Forest decline associated with air pollution and acid deposition is being studied using remotely sensed observations of the forest's state and change over time. Landsat and experimental airborne sensors are being used to acquire data on forest health, composition, structure, and canopy biochemical composition as a means of gathering information about the response of the forest and of inferring the possible proximal cause(s) of the decline response. These results should yield better understanding of the utility of remotely sensed data for studying stressed vegetation and of the effects of anthropogenic air pollution on forested ecosystems.

- *Tropical Deforestation.* To assess the areal extent and rate of deforestation in the tropics and to analyze its effect on regional ecological processes and climate. AVHRR data are being used to monitor large-scale deforestation and to observe the frequency, extent, and role of fires in tropical forest areas. Data from several different years are being analyzed to estimate the rate of deforestation in the southern Amazon Basin. This information is valuable for gaining insight into the severity of human impact on tropical forests and for assessing the potential loss of biological diversity in these regions. It will also provide information on changes in the surface energy budget for the region which can be used to assess feedbacks to the regional climate.

- *Desertification.* This research is intended to investigate the coupled vegetation-atmosphere response to stressful conditions resulting either from abnormal atmospheric conditions or land use pressure resulting from socio-economic and demographic conditions in semi-arid ecosystems. Retrospective analysis of historic satellite data and field, aircraft, and satellite studies of surface energy balance are being conducted. This research contributes to the global change initiative.

Solid Earth Processes

Focused ($2.2M)

Research

- *Earth Observing System (Eos).* Development of technology to study from polar-orbiting platforms solid Earth processes such as crustal deformation, surface topography, and surface composition.

Contributing ($47.3M)

Research

• *Tectonic Plate Movement and Deformation Processes.* The goal is to contribute to the understanding of the solid Earth, in particular the processes that result in movement and deformation of the tectonic plates. The approach is to make precise measurements of site and motion motions using results derived from satellite laser ranging (SLR), very long baseline interferometry (VLBI), the global positioning system (GPS), and, in the future, the Geodynamics Laser Ranging System (GLRS). These data are being collected and processed on a continuing basis. The pay-off will be a better understanding of the processes involved in tectonic movement and deformation and how these processes relate to earthquakes.

• *Earth's Rotational Dynamics Processes.* The goal is to develop models of polar motion, Earth rotation, and the dynamics of the Earth's interior. The approach is to evaluate data signatures extracted from satellite laser ranging (SLR), lunar laser ranging (LLR), very long baseline interferometry (VLBI), and the global positioning system (GPS). These investigations are in progress. The result will be a better understanding of the rotational dynamics of the Earth and their relation to changes in atmospheric angular momentum, earthquakes and other forms of mass redistribution.

• *Volcanology.* The goal is to document the distribution of current volcanic activity and recent volcanic deposits and study volcanic processes in order to develop a better understanding of contemporary volcanism-related earthquakes and volcanic eruptions. The approach uses a combination of satellite and aircraft observations including the Total Ozone Mapping Spectrometer (TOMS), AVIRIS, SAR, TIMS, LANDSAT, and SPOT with field and laboratory measurements to monitor certain kinds of volcanic activity and to study the history of flow and explosive volcanism. Through a better understanding of the patterns of volcanic activity it will be possible to evaluate the effects of volcanic activity on atmospheric composition, and through an analysis of volcanic hazard potential it should be possible to recommend means of mitigating volcanic hazard.

• *Geopotential Field.* The goal is to measure high resolution, extremely accurate, truly global gravity and magnetic fields to meet the requirements of geodesy, geodynamics oceanography, orbit determination and related disciplines. The approach is to support the acquisition, processing and analysis of ground-based, airborne, and space-based data. High priority is given to the initiation of the ESA/NASA gradiometer mission and the development of the Superconducting Gravity Gradiometer. The pay-off will be a significant contribution towards the understanding of Earth structure and dynamics.

• *Aircraft Operations:*

  • *Plate Tectonics and Continental Evolution.* Multi-sensor aircraft observations of surface structure and lithology and of the mineral composition of exposed rocks to infer the accretionary, depositional, tectonic, and deformational processes which shaped today's continents.

  • *Surface Mineral Composition.* High spectral resolution reflectance data from the Airborne Visible-Infrared Imaging Spectrometer (AVIRIS) to uniquely identify surface minerals and thereby infer the processes that emplaced them.

  • *Laser Altimetry.* Precise measurement using an airborne laser profiler to eludidate structural relationships and document roughness parameters in order to characterize surface processes.

Long-Term Observations

• *Laser Ranging*. The goal is making precise laser ranging measurements to (and from) satellites and the Moon for studies of the solid Earth. The approach is to support the collection and reduction of laser ranging measurements with high precision for geophysics applications. Laser ranging is an ongoing effort, with continued improvement in performance of the systems. The pay-off is in data that are precise enough for measurements of tectonic plate motion and deformation, and for studies of the rotational dynamics of the Earth.

• *Very-Long-Baseline Interferometry (VLBI)*. The goal is to use VLBI to provide an independent source of precise measurements of inter-site distances, and Earth orientation/rotation parameters. The collection and reduction of VLBI data has continued and is providing important geodetic results in the study of tectonic plate motion, plate boundary deformation and Earth rotation.

• *Global Positioning System (GPS)*. The goal is to use GPS signals to measure crustal movements and deformation in local areas of high earthquake activity, providing more dense coverage at lower cost. The approach is to use GPS signals to make precise measurements of relative positions of receivers situated near ground markers in areas of tectonic activity. Receivers capable of providing precise results have been developed and tested, and an expanding measurement program is in progress. The result will be a better understanding of crustal deformation along active plate boundaries and elsewhere.

• *Satellite Gravity Measurements*. The goal is to obtain accurate gravity field information for solid Earth studies. The approach is to use laser ranging, including drag-free satellites in low orbit, satellite altimetry and gradiometry. An active existing program in gravity field measurements will be greatly enhanced by the use of precise spaceborne gradiometers. The results will be gravity field data accurate enough for geophysics studies.

• *Magnetometer Field Measurements*. Use of satellite magnetometers to measure the intensity and direction of Earth's magnetic field to yield insight into core fluid dynamics, core-mantle boundary interactions, and deep crustal structure and composition. Both low orbit (for crustal studies) and high orbit, long-term monitoring (for secular variation) are required.

Data Management

• *Crustal Dynamics Data Information System*. Management of observational and reduced geodetic data for solid Earth studies.

• *Pilot Land Data System (PLDS)*. PLDS will play a significant role in future geological research and long-term activities related to the global change initiative. It currently offers a library of a wide range of mineral spectra and other surface-based, airborne and space-based geologic observations.

Solar Influences

Focused ($0.7M)

Research

• *Earth Observing System (Eos)*. Development of technology to measure from integrated polar-orbiting platforms to measure solar output, both of the total energy output and for specific wavelength regions (particularly ultraviolet).

Contributing ($7.7M)

Research

• *Upper Atmospheric Research Satellite (UARS).* To determine the variability of solar UV input in the wavelength range 115 - 430 nm. Two independent ultraviolet spectrometers flown aboard the UARS satellite. Construction and testing of satellite instruments and development of data analysis software. Improved understanding of solar variability as a driver in changing atmospheric composition and climate.

• *Payload and Instrument Development.* Development, testing and operation on Shuttle missions (Atmospheric Laboratory for Applications and Science[ATLAS]) of an active cavity radiometer to measure total solar output (solar constant).

• *Solar Irradiance Monitoring Program (SIMP).* The suite of Active Cavity Radiometer Irradiance Monitor (ACRIM) instruments flown aboard NASA Satellites since 1980 (SMM, space shuttle), and those to be flown in the future (UARS, Eos) are intended to provide a long-term (~22 year solar magnetic cycle) record of the variations in total solar output. These data will explore variations whose climatological significance requires long time scale observations.

National Science Foundation (NSF)

Climate and Hydrologic Systems

Focused ($13.2M)

Research

• *Tropical Ocean/Global Atmosphere (TOGA).* To describe the tropical oceans and global atmosphere, and the processes which connect them, as a time-dependent system in order to determine the extent to which this system is predictable on time scales of months to years. Studies include observations, data interpretations and simulations of the seasonal and interannual variability of the tropical ocean-global atmosphere system. TOGA's goal is the development and evaluation of predictive models of this system. This is an interagency and international program involving NOAA, NSF and NASA as well as 13 other nations. This program is expected to lead to better predictions of oceanic forcing, and its response and feedback to long-term changes in the atmosphere.

• *World Ocean Circulation Experiment (WOCE).* To understand the general circulation of the global ocean well enough to model its present state and predict its evolution in relation to long-term changes in the atmosphere and to provide the background for the long-term measurement of large-scale circulation in the ocean. This is a multi-agency program involving NSF, NOAA and NASA. A WOCE Hydrographic Office is being set up, and instrument development and testing is underway. This will set the stage for conducting the WOCE Hydrographic Program, a coordinated international field program for global and southern ocean studies. The long-term benefits expected from this program are improved models of atmospheric-oceanic coupling that can be used for climate simulation and prediction.

• *Arctic Systems Science (ARCSS).* To understand the natural interactions that link the arctic environment to global climate, geologic, and oceanic processes, with emphasis on biosphere- ocean-atmospheric processes and interactions in arctic regions. Activities include research on arctic oceanographic, biological, terrestrial and atmospheric processes and their relationships to global processes and climate change. This program will provide improved information and predictive modeling capabilities of physical and biological conditions and changes in the environmentally sensitive north polar regions of the planet.

Contributing ($42.2M)

Research

• *Environmental Research.* To provide support of fundamental research in hydrology, climate dynamics, meteorology, physical oceanography and glaciology that promotes and contributes to advances in the scientific knowledge and understanding of the Earth's physical environment. Activities include field, laboratory and theoretical studies of atmospheric, oceanographic, and cryospheric processes in polar, temperate and equatorial regions of the globe. This research investment contributes significantly to the scientific understanding of the Earth's atmosphere, hydrosphere and cryosphere and their interactions with each other. This research support also contributes to the education and training of future environmental scientists who will face the demanding challenges of conducting Earth system research.

Data Management

• *Environmental Data Bases.* To provide special data bases for use by the scientific community in climate research and modeling activities. Research on climate and hydrologic systems is heavily dependent upon the availability of observational data; for example, studies of El Niño and associated global relationships. The National Center for Atmospheric Research (NCAR) maintains a large organized archive of computer-accessible research observational data and analysis, that is used by scientists for national and international atmospheric and ocean research projects. This archive includes: National Meteorological Center daily analysis from 1946, data sets and monthly statistics of world ship observations (1854-1979), and satellite sounder data from 1968-1985. In addition, the Foundation supports data and sample repositories, such as the Antarctic Marine Core Repository.

Facilities

• *Climate Research Facilities.* To provide facility support for basic climatological and hydrological research studies. The collection of field observation data requires various field station, aircraft and ship support, and the requisite logistical support necessary to conduct glaciology and physical climate studies in the Antarctic region. These facilities are provided annually for competitively approved projects and permit comprehensive investigations of element of the hydrologic and climatic systems.

Biogeochemical Dynamics

Focused ($13.5M)

Research

• *Global Tropospheric Chemistry Program (GTCP).* To measure and model concentrations and distributions of gases and aerosols in the lower atmosphere; the chemical reactions among atmospheric species; sources and sinks of important trace gases and aerosols; and exchange of gases and aerosols between the troposphere and the biosphere, the Earth's surface, and the stratosphere. Activities include field, laboratory and modeling studies designed to better understand tropospheric oxidant chemistry; development of new instruments for measuring trace atmospheric constituents. Part of a multi-agency effort with NASA (Tropospheric and Stratospheric Chemistry) and NOAA (RITS and Acid and Oxidant Processes). Near and long-term benefits will be an improvement in understanding the processes controlling atmospheric composition and the ability to predict atmospheric chemistry changes and the resulting influences on the climate system.

• *Global Ocean Flux Studies (GOFS).* To identify and quantify the role of the ocean basins and coastal oceans in the global biogeochemical flux of the most important of the biologically active elements (C, N, O, P, and S). Activities include measuring the rates and processes of exchange between the ocean and atmosphere and ocean and land/ocean margins. A long time series of ocean data stations to characterize global change of ocean fluxes is being initiated in conjunction with NASA ocean color satellite sensor data, the first two being in the Pacific and Atlantic central gyres. Process-based ocean basin studies are being developed on an international level. The first of these is in the North Atlantic, in cooperation with NOAA, NASA, ONR, four European nations, and Canada. GOFS will develop a predictive ability to understand the effects of global-scale perturbations on the oceans' role in the flux of these elements, and conversely, the role these oceanic processes play in global change issues

• *National Ozone Expedition (NOZE).* To improve the understanding of stratospheric ozone chemistry, with particular emphasis on stratospheric depletion of ozone over the Antarctic, and the effects of increased ultraviolet radiation on biota in the high southern latitudes. An interagency program with NOAA and NASA aimed at obtaining observational and theoretical information on Antarctic Ozone depletion and the resultant changes in UV radiation exposure to biota. This program will lead to improved predicative capabilities for stratospheric chemistry and its biological significance in the high latitudes.

Facilities

• *Accelerator Mass Spectrometry Facility.* To provide the analytical capability to measure carbon-14 in small (i.e., 250 ml) seawater samples in support of GOFS objectives.

Contributing ($18.0M)

Research

• *Environmental Research.* To provide support of fundamental research in atmospheric chemistry, marine chemistry, and terrestrial and oceanographic biology that promotes and contributes to advances in the scientific knowledge and understanding of biogeochemical processes. Activities include field, laboratory and theoretical studies of biogeochemical processes in polar, temperate and equatorial regions of the globe. This research investment contributes significantly to the scientific understanding of basic environmental processes and the interactions that take place between the biosphere, hydrosphere, and atmosphere. This research support also contributes to the education and training of future environmental scientists who will face the demanding challenges of conducting Earth system research.

Facilities

• *Facility support* for basic biogeochemistry research studies. The collection of field observation data requires various field station, aircraft and ship support, and the requisite logistical support necessary to operate in the Antarctic region. These facilities are provided annually for competitively approved projects and permit comprehensive investigations of the biogeochemistry of the Earth's atmosphere and oceans.

Ecological Systems and Dynamics

Focused ($1.9M)

Research

• *Global Ocean Ecosystems Dynamics (GLOBEC).* To understand the response of marine plant and animal populations to environmentally driven changes in ocean circulation and chemistry induced by "greenhouse" warming and pollutants. Research will focus on (1) the role of animal populations in controlling and transforming global primary production (relating to GOFS), (2) the causes of interannual and decadal fluctuation of stocks of animal populations, including determination of the early life history events in affecting recruitment to adult populations including commercial fisheries, (3) the biological and economic implications of large-scale air/sea interactions (e.g. El Niño, relating to TOGA) involving marine populations, (4) the reasons for accelerating incidents of toxic algal blooms (red tides) and (5) the potential threat of global change to ocean biota diversity, the gene pool and its biotechnology implications. Essential to these goals will be development of advanced sampling technologies for real time analysis of population status, the establishment of long-term ocean ecological observation sites and the development of new ecosystem theoretical and numerical models. This program is cooperative with objectives of NOAA (NMFS, OAR, Sea Grant), NASA and the Office of Naval Research (ONR) in particular.

• *Land Margin Ecosystem Research (LMER).* To stimulate the basic interdisciplinary research necessary to determine how the many types of land sea interfaces (e.g. estuaries, salt marshes) act as integrated ecosystems rather than merely boundaries. Activities include the identification and quantification of the flux of materials, and their transformations, through these margin systems and how this contributes to the productivity of coastal oceans and the support the nursery grounds of important marine populations. This is expected to allow improved prediction of the consequences of global sea level rise on these rich ecosystems upon which human populations depend.

Contributing ($12.9M)

Basic Research Support.

• *Global Terrestrial Ecosystem Dynamics.* To determine how the terrestrial biota will respond to changes in the climate system and how biotic responses feed back to the climate system. Activities include studies of how the biosphere and atmosphere interact through biotic influence on composition and concentration of trace atmospheric constituents; and research on ecological responses to changes in environmental conditions. This will permit the improvement of ecosystem models for predicting ecological changes on long and short-term time scales, and how these changes might influence the regional or global environment.

• *Environmental Research.* To provide support of fundamental research in ecology, ecosystems dynamics, population biology, systematic biology, biological oceanography, and polar biology that promotes and contributes to advances in the scientific knowledge and understanding of ecology and ecological processes. Activities include field, laboratory, and theoretical studies of terrestrial and marine biology and ecology in polar, temperate, and equatorial regions of the globe. This research investment contributes significantly to the scientific understanding of the Earth's biosphere and its interactions with other elements of the environment. This research support also contributes to the education and training of future environmental scientists who will face the demanding challenges of conducting Earth system research.

Facilities

• *Long-Term Ecological Research Sites (LTER).* To provide research stations and the scientific infrastructure at selected natural and representative ecosystems for the conduct of long-term basic research on ecological phenomena. The current LTER network consists of 15 sites in the U.S. Planning for the development of two sites in the Antarctic is underway for the McMurdo and Palmer areas. The Antarctic sites are to be established in regions that are believed to be vulnerable to pronounced climatic and environmental change. Components of these LTER's investigate the physical and climate environment and trophic structure patterns and control. The benefits resulting from these facilities include a long-term data base for the different ecosystems and the ability to conduct comprehensive and ongoing ecological studies.

Earth System History

Focused ($2.0M)

Research

• *Arctic Systems Science (ARCSS).* To understand the natural interactions that link the arctic environment to the global climate, geologic, and oceanic processes, with emphasis on arctic paleoenvironments. The second Greenland Ice Sheet Project (GISP II) is underway which will provide more than 125,000 years of atmospheric climate history. This research activity will provide important information for defining and understanding how climate has varied in the past and determining how well the historical record can be explained and used for understanding future changes in the climate system.

Contributing ($22.0M)

Research

• *Paleoenvironmental Research.* To provide support of fundamental research in the Earth sciences, biology, paleontology and glaciology that promotes and contributes to advances in the scientific knowledge and understanding of the Earth's past environment. Activities include field, laboratory and theoretical studies of atmospheric, oceanographic, lithospheric and biospheric records in polar ice sheets and land and oceanic deposits. Basic geologic studies are supported to improve our understanding of the processes that control the change of the natural environment through space and time. The geologic record is the data base that stores the past history of environmental change. Specific studies using stratigraphy, sedimentology, paleontology, geomorphology, dendrochronology, and Quaternary geology are essential to understand the impact of changing environments on the world's climate and reasons for major extinctions of species. Data from previous environmental systems are the only mechanism for testing the efficacy of computer models for predicting future change. This research support also contributes to the education and training of future environmental scientists who will face the demanding challenges of conducting Earth system research.

• *Ocean Drilling Program.* The Ocean Drilling Program is an international effort that obtains cores of the Earth's crust beneath the oceans in order to reveal the composition, structure, and history of the submerged portion of the Earth's surface. The research focus is on potential drilling regions by means of geophysical field studies, development of downhole instrumentation and techniques, and geophysical and geochemical experiments. Operations are being conducted in the Western Pacific Ocean near the Sea of Japan, and will move into the Central Pacific later in the year. The program has sampled many sites, is nearing completion of a global circumnavigation, and future activities will be dominated by scientific thematic questions.

Facilities

• *Research Facilities.* To provide for support of the Ocean Drilling Program through operation of the JOIDES RESOLUTION drilling ship to carry out competitively approved sampling projects. Logistic support is provided for approved projects to scientists conducting research in the Antarctic.

• *Accelerator Mass Spectrometry Facility.* To provide the analytical capability to measure carbon-14 in small samples in support of geochronological studies in conjunction with: polar ice, lake sediments, tree rings, and solar terrestrial research.

Human Interactions

Contributing ($1.0M)

Research

• *Social Sciences Research.* To better understand the human dimensions of global environmental and climate change. Studies of teleconnections; atmospheric resources for development; climate variability and economic competitiveness and resource management; and the use of climate-related information will continue. Research on human influences on the environment and public and private sector responses to global change, including risk communication and management, will also be supported. Analysis of these factors will help focus the questions considered in climate modeling and improve the usefulness of scientific findings in other areas.

Solid Earth Processes

Focused ($6.2M)

Research

• *Landmass Movement.* To conduct high precision studies to directly monitor and measure the vertical and horizontal movements of landmasses. This activity will provide basic data on active changes for processes that control erosion through continental hydrologic processes, coastal flooding through sea level changes, and earthquakes that result through crustal strain and subsequent deformation. A major activity is to provide Global Positioning System receivers to the scientific community to make use of the DOD NAVSTAR satellite constellation.

• *Global Seismic Research.* To carry out high precision studies using a globally distributed wide-band digital network to measure seismic energy. This activity will provide basic data on active processes that produce global change on the short-term (such as volcanic explosions) and on the long-term (such as vertical and horizontal movement of landmasses). It also has the potential for increasing the understanding of the source and variability of the electromagnetic dynamo believed to be controlled by outer core and/or core-mantle processes. Changes in the Earth's magnetic field, especially reversals, can have major but as yet unknown effects on humans and other biological forms. A major activity is the purchase, distribution, and operation of the instruments for the Global Seismic Network.

• *Active Tectonics.* To carry out field experiments in active tectonics. This activity will provide basic data on geologically common phenomena that occur on the scale of years to decades to centuries. A major activity is to use the instrumental arrays previously described as well as standard field techniques.

• *Ridge Inter-Disciplinary Global Experiment (RIDGE).* To understand the physical, chemical, and biological causes and consequences of the energy transfer within the global mid-ocean ridge system through time. Research will quantify the flow of mantle material, the generation of melt, and the emplacement of molten rock along mid-ocean ridges; the transformation of molten magma into oceanic crust; the segmentation and episodic accretion of oceanic crust; the physical and chemical interaction between circulating seawater and oceanic crust; the biological interactions within ridge-related hydrothermal systems; and the temporal/spatial variations of mid-ocean ridge venting and its influence on the oceanic environment.

Contributing ($9.7M)

Research

• *Geology Research.* To provide basic knowledge to understand the structure, composition and formation of the continents. Research includes study of processes that shape the surface of the continents and determine the interactions between the solid Earth, biosphere, atmosphere and oceans. Activities include major geophysical and drilling programs managed by the Continental Lithosphere Program and support of research in Arctic tectonics. To increase understanding of the formation, structure, and history of the 70 percent of the Earth's surface covered by oceans. Research to test and further the predictive capabilities of the plate tectonic paradigm and to understand the processes responsible for the formation and morphology of the ocean crust. This research support also contributes to the education and training of future environmental scientists who will face the demanding challenges of conducting Earth system research.

Solar Influences

Focused ($2.4M)

Research

• *Coupled Energetics and Dynamics of Atmospheric Regions (CEDAR).* To understand the energetics, dynamics and latitudinal and vertical coupling between the upper and middle atmosphere. Activities include field campaigns utilizing optical and radar equipment to generate an observational data base in coordination with theoretical studies for the development and evaluation of global models of the upper atmosphere. This program is expected to produce improved models of the coupling of solar energy into the upper atmosphere and how this in turn influences the global climate system.

• *National Ozone Expedition (NOZE).* To improve the understanding of stratospheric ozone chemistry, with particular emphasis on stratospheric depletion of ozone over the Antarctic, and its effect on the fluxes of ultraviolet radiation in the high southern latitudes. An interagency program with NOAA and NASA aimed at obtaining observational and theoretical information on Antarctic Ozone depletion and the resultant changes in UV radiation. This program will lead to improved predicative capabilities for stratospheric chemistry and its biological significance in the high latitudes.

Data Management

• *Cedar Data Base.* A data management base consisting of upper atmosphere observations obtained with incoherent scatter radars and optical instruments is maintained at NCAR. These data include CEDAR field campaign collections, and data collected at four incoherent scatter radar facilities support by NSF and several European facilities.

Contributing ($6.6M)

Research

• *Solar Terrestrial Research.* To provide support of fundamental research in aeronomy, solar terrestrial physics, and magnetospheric physics that promotes and contributes to advances in the scientific knowledge and understanding of the Earth's upper atmosphere and the near space environment. Activities include field, laboratory and theoretical studies of upper atmosphere and solar processes that influences the Earth's environment. This research investment contributes significantly to the scientific understanding of the solar influence on atmospheric dynamics and composition. This research support also contributes to the education and training of future environmental scientists who will face the demanding challenges of conducting Earth system research.

United States Department of Agriculture (USDA)

Climate and Hydrologic Systems

Focused ($1.5M)

Research

• *Water Yields, Erosion and Sedimentation.* The goal is to relate potential changes in physical and chemical climate properties to the water yield by studying forest to non-forest transitional areas and associated small changes in temperature with or without precipitation and the influence of vegetation.

Contributing ($8.1M)

Research

• *Watershed.* The objective is to refine the water budget and waterflux between the atmosphere-pedosphere-geosphere for selected agricultural ecosystems, especially those where minimum or no-till tillage systems are being employed.

• *Snow Surveys.* The goal of the SNOTEL snow courses and remote telemetry sites is to monitor snow pack and its water content to assist in forecasting water, usually in the Western U.S. The data transmission technology is capable of handling additional site parameters.

Biogeochemical Dynamics

Focused ($2.1M)

Research

• *Carbon, Water, and Nutrient Cycling.* The goal is to better understand the geochemical processes mediated by bacteria and fungi and their adaptability to changing environmental conditions. A major concern is that acclimation will occur within broad limits, but once thresholds are exceeded, an ecosystem and its capabilities in cycling biogeochemical elements may change drastically.

Contributing ($4.7M)

Research

• *Cycling and Steady State Levels of Carbon, Nitrogen, Phosphorus, and Sulfur.* The goal is to model the biogeochemical process of major nutrient cycles in terms of influence by variables of temperature, precipitation, soil texture, soil management practices, and vegetation.

• *Assimilation of CO_2.* The goal is to understand the growth and water use by crops at CO_2 levels expected in the future. Growth and water use efficiency are determined as a function of CO_2 and temperature for several field crops and some trees.

• *Acid Deposition.* The goal is to understand the basic process of biogeochemical cycling and the buffering capacity of soil, lake, stream and forested watersheds as affected by atmospheric deposition. This knowledge will be used to predict ecosystem resiliency to acid deposition.

• *CO_2 Effects*. The goal is to determine whether increasing CO_2 in the atmosphere partially explains the invasions of grassland C_4 species by woody C_3 species.

Ecological Systems and Dynamics

Focused ($14.7M)

Research

• *Species Life Histories and Distribution, and Community Composition.* The goal is to understand how important biological population processes such as seed production, natural seedling establishment and tree death are influenced by atmospheric conditions. Alteration of one or more of the key population processes would lead to changes in community composition and eventually to changes in distribution of individual species. This research supports development of future timber supply prediction models.

• *Effects of Ozone*. The goal is to establish critical levels of exposure and sensitivity of non-dominant forest species, and to understand the mechanism of ozone injure. Moderate to high levels of ozone have caused selective death of forest tree species and thus significant changes on forested ecosystems. These levels of ozone are widely distributed across the country. The critical level of ozone, alone or combined with other pollutants, can lead to physiological and anatomical changes resulting from either long-term low level or short term high level exposures.

• *Forest Fire Sensitivity and Occurrences.* The objective is to better relate forest fire intensity and damage to vegetation amount and structure, moisture content of fuels and weather conditions as well as forest composition and frequency and severity of drought.

• *Aquatic Ecosystems and Fisheries.* The goal is to determine physical and chemical response characteristics of lakes and streams that may vary with projected climate changes.

• *Wildlife and Domestic Species of Animals.* The objective is to examine changes in wildlife populations as integral parts of landscapes that could occur due to shifts in seasonal range carrying capacity resulting from projected climate changes.

• *Microbes, Plant Pathogens, and Insects.* The goal is to determine how differential environmental stresses on insect and pathogen populations alter the frequency and sensitivity of insect and disease outbreaks.

• *Effects of UV-B*. The goal is to examine growth at elevated levels of UV-B radiation and determine mechanisms by which damage is inflicted.

• *Assessment of Biological Responses to Increased UV-B*. The goal is to study biological responses and mechanisms of responses at physiological, biochemical, cellular and molecular levels of agricultural and forest plant systems.

Long-Term Observations

• *Long-Term Ecosystem Modeling*. The objective is to establish long-term trends in forest health and productivity and establish a baseline state of forest health. Large, long-term data bases have been established from monitoring on experimental forests and rangelands. In addition, forest inventory has established long-term timber supply trends. Forest pest surveys document major outbreaks of pests. A long-term program is needed which assures that monitoring addresses: (1) representative ecological units, (2) accumulated data can be compared globally, (3) appropriate parameters are measured simultaneously and (4) sampling continues well beyond the life span of the dominant organism.

Contributing ($19.6M)

Research

- *Forest Fire and Atmospheric Sciences.* The goal is to broaden the basic knowledge of forest atmosphere interactions with research on basic processes of fire behavior, fire effects, fire danger, fire weather and effects of air pollutants from burning.

- *Forest Insect and Disease.* The goal is to understand the basic biological process of insect and disease outbreaks and associated host-predator relations.

- *Wildlife and Fisheries.* The goal is to understand habitat requirements of different species and how different species may compete for habitat as global changes take place.

- *Monitoring.* The goal is to utilize preferred plant species and grazing lands and growth stress response of trees to indicate how global change stresses may be addressed.

- *Spatial Patterns of Kinds of Soils.* The objective is to locate and inventory areas where soil properties and conditions of formation and development have been similar. Activities include identification, classification and mapping of soil patterns and collection, analysis and evaluation of soils in survey areas. Detailed soil maps at a scale of about 1:20,000 with generalized soil maps at a scale of 1:250,000 for the U.S. are in different stages of preparation.

- *Agricultural Chemicals Research.* The goal is to trace pesticides and other agricultural chemicals through agro-ecosystems and forest and range ecosystems, modeling their transformations and effects, and assessing ecosystem-level risk associated with them as global changes take place. Research will include practices that produce optimum pest control or plant response from minimal quantities of applied chemicals for specified environmental conditions.

Data Management

- *Soils Data Bases.* The objective is development and maintenance of computerized data bases on the kinds of soils and their mapping unit distributions by counties. Field descriptions of soils and laboratory data are being reorganized to facilitate their use by other organizations. Some digital maps and text material are also being prepared. Soil pedon data for selected soils in the tropics are part of a World Soil Database being developed. They provide a consistent set of physical and chemical data of important soils in tropics and subtropics.

Earth System History

Contributing ($0.7M)

Research

- *Natural Variability of Soil Cover.* A major goal of soil survey research is to demonstrate the spatial variability and distribution of soils and their properties. Scales vary from county level to state and national generalizations. Qualitative models of soil formation and landscape evolution form the basis for mapping the soil resources and there is great potential to develop quantitative models to assist in the understanding of biogeochemical cycles and patterns and behavior and extend to ecosystems in the past.

Data Management

- *Geographic Information Systems.* The objective is to develop and maintain activities capable of linking geographic soil patterns with climatic, geomorphic and other data layers (land use, topography, etc.) to better understanding scales and patterns of variability. Research is being identified to determine scalar relationships that explain the global patterns of soil cover.

Human Interactions

Contributing ($25.2M)

Research

• *Predicting Effects of Weather and Air Quality.* The goal is to conduct research contributing to new technology capable of accurately predicting the effects at the meso or micro geographic scale of weather and air quality for agricultural productivity.

• *Optimizing Water Use by Plants.* The goal is to conduct research contributing to new technology for optimizing limited irrigation water or use of rainfall to stabilize productivity of agro-ecosystems and rangeland ecosystems.

• *Groundwater Research.* The goal is to conduct research on management of agricultural chemicals, natural fertilizers and soil movement of nutrients and chemicals to minimize groundwater contamination and atmospheric losses through new technology to improve irrigation scheduling and minimizing leaching.

Long-Term Observations

• *Natural Resources Inventory.* Periodic assessment of the condition and changes of privately owned land resources, including range conditions, soil erosion, and kinds of land use in the U.S. are obtained in more than 300,000 sample units. Information is used in Resource Conservation Act assessments on 5- and 10-year intervals.

• *Resource Planning Assessment.* Renewable Resources Planning Act requires USDA (FS) to conduct periodic assessments of condition and treads of publicly administered lands in the U.S.; including data on land cover and productivity of forests. The information is used in nation-wide renewable resources assessment on 5- and 10-year intervals.

Solid Earth Processes

Contributing ($91.1M)

Research

• *Small Watershed Processes.* The goal is to conduct research that supports models of hydrology in landscapes. This provides an understanding of how land surface changes are reflected in natural soil variability. Geomorphic surfaces and sediments are crucial to unravelling the patterns of existing high-contrast soils that occur side-by-side.

APPENDIX C

CHARTER
COMMITTEE ON EARTH SCIENCES
of the
Federal Coordinating Council for Science, Engineering, and Technology

The Committee on Earth Sciences (CES) is hereby established by action of the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET). FCCSET derives its current authority from Executive Order 12039 of February 24, 1978.

Purpose and Functions

A goal of Earth sciences is to understand, on a global scale, how the highly interactive system comprised of the solid Earth, the oceans, the atmosphere and magnetosphere, and the biosphere has evolved, how it functions today, and how it will evolve in the future. In addition to the basic research, important components of Earth science R&D include continued development of the technology for needed observations of the Earth system and increased emphasis on collection, analysis and archival of data on a global scale from satellite and ground-based measurements needed for long-term research efforts and also needed to address national policy issues which depend on a characterization of humankind's impact, or potential impact, on the global environment. The purpose of the Committee on Earth Sciences is to increase the overall effectiveness and productivity of Federal R&D efforts directed toward an understanding of the Earth as a global system. In fulfilling this purpose, the Committee addresses significant national policy matters which cut across agency boundaries.

Specifically the CES:

a. reviews Federal R&D programs in Earth sciences including both national and international programs;
b. improves planning, coordination, and communication among Federal agencies engaged in Earth sciences R&D;
c. identifies and defines Earth sciences R&D needs;
d. develops and updates long-range plans for the overall Federal R&D effort in Earth sciences;
e. addresses specific programmatic and operational issues and problems which affect two or more Federal agencies;
f. provides reviews, analyses, advice and recommendations to the Chairperson of FCCSET on Federal policies and programs concerned with Earth sciences R&D, particularly in assessing humankind's impact on the global environment;
g. develops the Administration's response to the call for a report to Congress, in the NSF Authorization Act of 1987, concerning Federal Government action with respect to the establishment of an International Year of the Greenhouse Effect mandated in calendar year 1991.

Structure

The Chairperson and Vice-Chairperson of the CES are appointed by the Chairperson of FCCSET; the Vice-Chairperson is from an agency other than that which the Chairperson represents. The Executive Secretary is designated by the CES Chairperson. Additional staff assistance is provided by member agencies as required by the Committee. Chairpersons of CES task forces or working groups arrange assistance from their own agencies.

The following departments and agencies are represented on this Committee:

Department of Agriculture
Department of Commerce
Department of Energy
Department of the Interior
Department of State
National Science Foundation
Environmental Protection Agency
National Aeronautics and Space Administration
Office of Science and Technology Policy
Office of Management and Budget
Council on Environmental Quality

Other Federal agencies participate, as appropriate, upon invitation by the Committee Chairperson or the Chairperson of FCCSET.

The CES Chairperson approves the establishment, continuation, or termination of task forces and working groups as necessary to achieve the Committee's purposes. Membership on such task forces and working groups is not restricted to Committee members and is established as the Committee may determine appropriate.

The Committee meets at the call of the CES Chairperson who also approves the agenda. Meetings are held not less than two times a year. Meetings of task forces and working groups are held as necessary to meet their specific objectives. Minutes of meetings are prepared by the Committee Executive Secretary and distributed to all members of the Committee, the leaders of task forces and working groups, and to the Executive Secretary of FCCSET.

Compensation

All members are full-time Federal employees who are allowed reimbursement for travel expenses by their agencies plus per diem or subsistence while serving away from their duty stations and in accordance with standard governmental travel regulations.

Documentation

Agendas and records of actions of Committee meetings are prepared and disseminated to members by the Executive Secretary. Records of actions are submitted to members for approval. Complete records of all Committee activities, including those of task forces and working groups, are maintained in the office of the Chairperson. The Committee prepares a report for the Chairperson of FCCSET not later than 60 days after the end of each fiscal year. The report contains, as a minimum, the Committee's functions, a list of members and their business addresses, the dates and places of meetings, and a summary of the Committee's activities and recommendations during the year.

Termination date

Unless renewed by the Chairperson of FCCSET prior to its expiration, the Committee on Earth Sciences of FCCSET shall terminate not later than December 31, 1990.

Determination

I hereby determine that the formation of the Committee on Earth Sciences is in the public interest in connection with the performance of duties imposed on the Executive Branch by law and that such duties can best be performed through the advice and counsel of such a group.

Approved:

March 6, 1987
Date

William R. Graham
Chairman, FCCSET

Appointment of New Member
and Amendment to the Charter
of the
Committee on Earth Sciences
(FCCSET)

APPOINTMENT: By my authority as Chairman, Federal Coordinating Council for Science, Engineering, and Technology (FCCSET), I appoint the Department of Transportation as a permanent member of the Committee on Earth Sciences (CES).

AMENDMENT: Charter of the Committee on Earth Sciences of the Federal Coordinating Council for Science, Engineering, and Technology as signed and approved on March 6, 1987, by the Chairman, FCCSET, is amended as follows.

Under the Section "Structure," add the following new member:

"Department of Transportation"

August 24, 1988
Date

William R. Graham

William R. Graham, Chairman
Federal Coordinating Council
for Science, Engineering,
and Technology

The U.S. Global Change Research Program