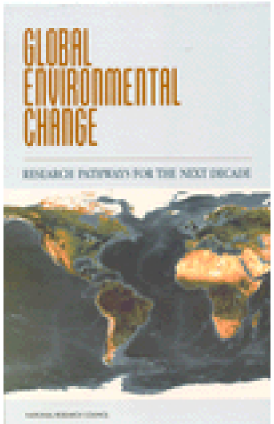

Global Environmental Change: Research Pathways for the Next Decade

Committee on Global Change Research, National Research Council

ISBN: 0-309-51780-X, 616 pages, 6 x 9, (1999)

GLOBAL ENVIRONMENTAL CHANGE

Research Pathways for the Next Decade

Committee on Global Change Research

Board on Sustainable Development

Policy Division

National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C.

NATIONAL ACADEMY PRESS • 2101 Constitution Avenue, N.W. • Washington, D.C. 20418

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was supported by Contract Nos. 50-DKNA-5-00015 and 50-DNKA-7-90052 between the National Academy of Sciences and the National Oceanic and Atmospheric Administration. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

Library of Congress Cataloging-in-Publication Data

Global environmental change : research pathways for the next decade / Committee on Global Change Research, Board on Sustainable Development, Policy Division, National Research Council.
p. cm.
Includes bibliographical references and index.
ISBN 0-309-06420-1 (hardcover : alk. paper)
1. Global environmental change. 2. U.S. Global Change Research Program. 3. Climatic changes—Research—United States. 4. Global warming—Research—United States. 5. Greenhouse effect, Atmospheric—Research—United States. I. National Research Council (U.S.). Committee on Global Change Research.
GE150 .G56 1999
363.738′74′072073—dc21
99-6463

Additional copies of this report are available from the National Academy Press, 2101 Constitution Avenue, N.W., Lockbox 285, Washington, D.C. 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); http://www.nap.edu

Printed in the United States of America

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Acknowledgment of Reviewers

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We thank the following individuals for their participation in the review of this report:

Ian Burton, Environmental Adaptation Research Group, Downsview, Canada
Antony J. Broccoli, Princeton University, Princeton, New Jersey
Radford Byerly, Roberts Institute, Boulder, Colorado
Robert A. Frosch, Harvard University, Cambridge, Massachusetts
Richard M. Goody, Harvard University, Cambridge, Massachusetts
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Donald F. Hornig, Harvard School of Public Health, Cambridge, Massachusetts
Charles F. Kennel, Scripps Institution of Oceanography, La Jolla, California
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Harry F. Lins, U.S. Geological Survey, Reston, Virginia
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While the individuals listed above provided many constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring committee and the NRC.

Preface

In the coming century a human population perhaps twice as large as today's will have to navigate a sustainable path through the ever-changing landscape of this small planet. Knowledge gleaned by science will be its best beacon and provide its soundest navigational chart. Science itself faces its own navigational challenges, as questions of growing complexity and richness abound while financial resources are limited. Scientists confront not only these research obstacles but also the urgent call from politicians and policy makers who seek guidance in reaching major decisions. As this report was being prepared, for example, representatives of many nations gathered in Kyoto, Japan, to forge an agreement on goals to cut greenhouse gas emissions. Such agreements set environmental goals, which will clearly affect scientific priorities as well as economic paths in the coming decade.

Thus, science needs its own clear framework through which to focus its energies. This intellectual framework is required to hone questions that need immediate attention, to separate the vital from the interesting, and to preserve basic research for discovery of the unexpected. In this report the Committee on Global Change Research (CGCR) provides guidance on such a framework by clarifying especially promising pathways for the planning of future U.S. research on global environmental change. An overview document was released by the committee in 1998 that summarized the background, findings, and recommendations of the report. The foundation of the report's recommendations includes the accumulated knowledge of worldwide scientific research over the past decade and especially that of the U.S. Global Change Research Program (USGCRP).

The CGCR was charged with reviewing the current status of the USGCRP with a view toward defining the critical scientific questions in the Program's four areas of concentration (seasonal to interannual climate prediction, decadal to centennial climate change, atmospheric chemistry, and terrestrial and marine ecosystems) and with preparing a report that would (1) articulate the central scientific issues posed by global environmental change; (2) state the key scientific questions that must be addressed by the USGCRP; and (3) identify the scientific programs, observational efforts, modeling strategies, and synthesis activities needed to attack these scientific questions. This report traces the scientific roots and programmatic development of the USGCRP, highlighting some of the lessons learned that help point to the most appropriate pathways ahead. The committee calls for a revitalization of the USGCRP, recognizing the need for a more sharply focused scientific strategy and a more coherent programmatic structure and stressing the importance of U.S. leadership in supporting global change research.

CGCR's study was undertaken in the context of intense national and international debate about the nature of global environmental change, particularly about the characteristics and potential impacts of climate change. This context is sharpened in several questions raised by the scientific community and the public at large:

- *The science*. In light of the U.S. Administration policy and agreements at the Kyoto conference, are not the causes of global change sufficiently clear and therefore should not the USGCRP now concentrate on the science related to mitigation measures?
- *The strategy*. What is the appropriate science strategy for resolving uncertainties about global environmental change? Are changes in the current strategy needed? If so, why (what has changed)? What are the crucial differences between any proposed new strategy and the existing strategy, and how do we make a transition from one to the other?
- *The implementation.* How can this strategy be implemented in terms of programs? Who will develop the priorities? When will this happen?

THE SCIENCE

It would be a misinterpretation of U.S. administration policy and agreements at the Kyoto conference to conclude that the causes and characteristics of global change are sufficiently clear that scientific inquiry in this area should be limited to mitigation measures. The agreements at the Kyoto conference are based on a general understanding of some causes and characteristics of global change; however, there remain many scientific uncertainties about important aspects of climate change. If the United States were to abandon or significantly reduce current research programs, the remaining scientific uncertainties would persist. In addition, it would be difficult to have confidence that mitigation measures were addressing the underlying causes.

It is true that the forcing terms of global change are being more clearly resolved. For example, the flux of greenhouse gases from industrial activities is reasonably well established; the rates and geographical distributions of the mobilization of other chemical compounds also are becoming clearer; and quantitative patterns of land-use change are being elucidated. In addition, significant progress has been made in understanding the lifetimes in the atmosphere of key chemical species such as greenhouse gases. We understand better the chemical and physical interactions that lead to the loss of ozone in the stratosphere and the production of ozone in the troposphere. We have begun to make considerable progress in characterizing patterns of climate variability, with one noted accomplishment being the successful prediction of the most recent El Niño event well in advance of its greatest impacts. And, although on a very limited basis, we have begun to investigate the possible impacts of various climate change scenarios on terrestrial systems by using global models of those systems.

A great deal more needs to be understood, however, about global environmental change before we concentrate on "mitigation" science. We do not understand the climate system well enough to clarify the causes and likelihoods of rapid or abrupt climate changes. What does the record from the past reveal *in detail* about environmental changes? What will be the patterns and modes of human-forced climate changes? What will be the impacts of multiple stresses on systems; in other words, what are the effects on terrestrial ecosystems of changes in the chemistry of the atmosphere, changes in the patterns and intensities of land use, and changes in temperature and rainfall patterns? How will the chemistry of the atmosphere be affected by continuing patterns of human-induced forcing, and how will these changes be affected by climate variability and change? What is the geographical distribution of the sources and sinks of greenhouse gases and how might they change? How will institutions respond to climate and other environmental changes? These are the types of scientific unknowns that require clarification if we are to make sound policy decisions; they are also the questions that must be answered if we are to have a sound foundation for mitigation science.

THE STRATEGY

The current science strategy was developed in concert with the initial planning of the USGCRP and was based on the view that what was most needed was a broad attack on understanding the Earth as a system. This has been a valuable and intellectually exciting goal, but it has also made the program too diffuse and left it vulnerable. When budgets ceased to expand and began to contract, the Program was not well grounded or well integrated enough to scale back in a logical way. The concept of an Earth system science view of the Program simply could not weather the budget process, which demanded greater specificity and accountability. Moreover, the need for prioritization—which should be one benefit derived from taking a systems viewpoint—has proved to be exceedingly difficult to achieve in practice. Finally, gains in understanding over the past 10 years and changes in the perceived requirements for research (i.e., results are now seen to be needed sooner rather than later, and key issues are now in need of resolution) must be recognized in a new strategy. It is, therefore, time to shift course; we are no longer simply building a ship but steering it, too. Given all that we know, these course corrections are necessary to reach our destination, and they will require retrofits in the hardware and navigational aids to improve speed and efficiency.

Resources and time are again in finite supply. We must concentrate scientific talents, observational capabilities, and modeling teams. Achieving these goals calls for an alternative strategy—one focused on answering specific, central scientific questions about global change. In fact, *our current inability to answer these scientific questions is seriously blocking progress in critical policy development as well as hindering the development of a more systemic view of the planet*. Thus, the committee recommends shifting to a scientific strategy of greater focus and sets forth corresponding pathways for research, observations, data systems, and modeling.

THE IMPLEMENTATION

To implement a new strategy effectively, the USGCRP, working closely with the Office of Management and Budget and the Office of Science and Technology Policy (OSTP), must develop initiatives based directly on the research imperatives, scientific questions, and crosscutting elements described in this report. Recommendations regarding the observational strategy, technological development, data and information systems, and modeling should be explicitly addressed by the USGCRP and OSTP.

Establishing the necessary observational systems will be especially challenging. They are likely to be expensive; their components must serve the needs of several different communities and act as a bridge between research and operational lines; and their design must be more robust in the face of changes in financial support. The National Aeronautics and Space Administration's (NASA) Earth Observing System (EOS) polar platforms—initially, EOS AM-1, EOS-PM-1, and EOS CHEM-1—were conceived as broadly-scoped data-gathering systems. This foundation will be central for needed future missions and will set the baseline for a long-term operational environmental monitoring program that must be built on the operational weather and ozone-observing system of the National Oceanic and Atmospheric Administration, the U.S. Department of Defense, and their international partners. To further the advances of the first three polar platforms, the committee calls for restructuring EOS to obtain data relevant to the Research Imperatives and unanswered Scientific Questions identified in this report, through smaller and more focused missions along the lines of the new Earth System Science Pathfinders. Moreover, some aspects of the observational systems must address three crosscutting scientific themes that are also fundamental to scientific understanding and policy: clarifying the Earth's carbon and water cycles; characterizing climate change on temporal and spatial scales relevant to human activities; and elucidating the connections among radiation, dynamics, chemistry, and climate. These achievements will require good in situ observational systems as well as space-based systems. The committee also recommends maintaining existing critical global observations that could be threatened by budget reductions, while designing a more coherent and balanced data and observational strategy for the future to capitalize on technological innovations.

As in all science, the task is not complete. Given the recommendations provided in this report, *the next task is to review and map the USGCRP activities against the set of Research Imperatives and unanswered Scientific Questions identified here, to help set optimal programmatic priorities*. This step should be the next effort of the Committee, its partners in the National Research Council (NRC) complex, and USGCRP agencies.

The NRC parent board of this committee, the Board on Sustainable Development (BSD), is seeking to develop its own scientific and intellectual strategy for the transition of our nation and indeed our global society to a sustainable future. This CGCR report will help guide the BSD's emerging agenda for research on the closely linked issues of energy, environment, and society—an agenda that will be needed to successfully navigate the transition toward sustainability.

ACKNOWLEDGMENTS

A study like this one, of such broad coverage, would not have been possible without assistance from many notable experts (see Appendix C). In addition to the persons listed earlier, the following NRC committees also contributed to the report: Committee on Human Dimensions of Global Change; Committee on Geophysical and Environmental Data; Climate Research Committee and its panels on the Global Ocean-Atmosphere-Land System, Climate Variability on Decade-to-Century Timescales, and Global Energy and Water Cycle Experiment; Ecosystems Panel; Board on Atmospheric Sciences and Climate; Ocean Studies Board; and Committee on Atmospheric Chemistry.

Speaking for both the BSD and the CGCR, we especially want to thank Dave Goodrich for working on the early drafts; John Perry for providing a link between the past and the present; Mark Dafforn, Suzanne Wilhelm, Laura Sigman, and Claudette Baylor-Fleming for editorial work on complicated copy; and Shere Abbott and Sylvia Edgerton for picking up the pieces and completing the project.

EDWARD A. FRIEMAN, *Chairman*
Board on Sustainable Development

BERRIEN MOORE III, *Chairman*
Committee on Global Change Research

Contents

1

Introduction and Background

SUMMARY

During its first 10 years of operation, the U.S. Global Change Research Program (USGCRP) has advanced our understanding of the Earth's ever-changing physical, chemical, and biological systems and the growing human influences on these systems. On the basis of this knowledge we can now focus attention on the critical unanswered scientific questions that must be resolved to fully understand and usefully predict global change. Such capability is increasingly important for developing our economy, protecting our environment, safeguarding our health, and negotiating international agreements to ensure the sustainable development of the United States and the global community of nations. There are now compelling reasons for scientific knowledge to guide and respond to policy options, both current and future. Clearly, we must delineate research pathways that will enlarge our understanding of changes in the global environment, including climate change. At the same time we need to reduce uncertainties in the projections that shape our decisions for the future. For all these reasons it is essential that the USGCRP continue to receive strong financial support and continue to provide continuing strong *scientific leadership.* To be effective the USGCRP must be based on a sound *scientific strategy,* focused on key unanswered *scientific questions,* using a correspondingly balanced strategy for supporting observational, data management, and analysis activities.

On the basis of the continuing reviews of the Committee on Global Change Research (CGCR) and those of its collaborating bodies, the committee reaffirms the achievements and significance of the USGCRP while finding that the Program must now be revitalized, focusing its use of funds more effectively on the

principal unanswered scientific questions about global environmental change. This goal demands that funding and efforts be directed toward a coherent and coordinated suite of research activities and supporting observational, data management, and modeling capabilities, all aimed at imperative research objectives and clearly defined scientific questions. *A sharply focused scientific strategy and a coherent programmatic structure are both critically needed.* This report seeks to provide a framework for such a strategy and structure. The elaboration and implementation of this scientific strategy and programmatic structure will be the principal challenge for global change research over the course of the next decade.

BACKGROUND

Long before the industrial revolution, human activity began to alter the Earth's environment. However, only in this century has the scale of such alterations become global in scope; moreover, the rate of these recent changes is enormously high compared with the historical record. Today, on the threshold of a new millennium, it is clear that humans are inducing environmental changes in the planet as a whole. In fact, the human fingerprint is abundantly seen on the global atmosphere, the world oceans, and the land of all continents. This insight has brought about profound changes in the goals, priorities, and processes of both science and government.

Programmatic Development

Recognition that humans are causing global changes in the biology, physics, and chemistry of the environment—changes with immense significance for human society and economy—has prompted the U.S. government, and other national governments, to act. In 1990, Congress established the USGCRP to carry out an organized, coherent attack on the scientific issues posed by global environmental change.

The USGCRP had its principal roots in the 1980s, as both scientists and the public became increasingly aware of the links among human activities, current and future states of the global environment, and human welfare. The most immediate concerns were human-induced climate change, stratospheric ozone depletion from industrial emissions, and emerging evidence that the Earth's biogeochemical system was being perturbed by a broad range of human actions.

Some of the many antecedents of the USGCRP were seen still earlier. In the 1970s a convergence of long-standing scientific concerns (see below) and a series of climatic events led to the first World Climate Conference and to the establishment of the U.S. National Climate Program and the World Climate Program.[1] In parallel, beginning in the mid-1970s, the U.S. Department of Energy (DOE) organized a major research program to assess the consequences of fossil-based energy production. Workshops chaired by the late Roger Revelle outlined a broad multidisciplinary research agenda closely congruent with today's USGCRP, including a strong emphasis on the carbon cycle, the role of ecosystems, and human dimensions research.[2]

> "If we believed that the Earth was a constant system in which the atmosphere, biosphere, oceans, and lithosphere were unconnected parts, then the traditional scientific fields that study these areas could all proceed at their own pace treating each other's findings as fixed boundary conditions. However, not only is the Earth changing even as we seek to understand it—in ways that involve the interplay of land and sea, of oceans, air, and biosphere—we cannot even presume that global change will be uniform in space and steady in time . . . . Needed to resolve this complex of change and interplay are coordinated efforts between adjacent scientific disciplines and programs of synoptic observations focused on common, interrelated problems that affect the Earth as a whole."—National Research Council (1983a)

The immediate precursor of the USGCRP, however, was a workshop sponsored by the National Aeronautics and Space Administration (NASA) in 1982 on global habitability, which was led by Richard Goody.[3] This workshop emphasized the fact that in many critical respects the ocean, atmosphere, and biosphere function together on long timescales as a single integrated system, a system requiring interdisciplinary research and observing programs of global scope and decadal duration. The stage had been set for encouraging similar fully integrated, long-term research by the Global Atmospheric Research Program, a program that itself arose from a seminal study by the National Research Council (NRC)[4] and laid the groundwork for the World Climate Research Program. The shaping of such comprehensive endeavors, which arose by recognizing the importance of chemical and biological as well as physical factors in the global system, also led to the establishment of the International Geosphere-Biosphere Program of the International Council of Scientific Unions (subsequently renamed the International Council for Science). The priorities and nature of this program, from a U.S. perspective, were laid out in a sequence of NRC reports.[5] Most recently, human components in global environmental change have been given wider recognition in the creation of the International Human Dimensions Program on Global Environmental Change.

> The goal of the International Geosphere Biosphere Program (IGBP) is "—to describe and understand the interactive physical, chemical and biological processes that regulate the total Earth system, the unique environment that it provides for life, the changes that are occurring in this system, and the manner in which they are influenced by human actions."—International Council of Scientific Unions (1996)

Still other precursors to the USGCRP include two reports in the 1980s by the NASA-sponsored Earth System Sciences Committee (ESSC),[6] which sought to define a new and revolutionary scientific discipline of Earth system science. In keeping with the Goody report[7] and the 1986 NRC report, *Global Change in the Geosphere-Biosphere,*[8] this new discipline would be dedicated to study of the Earth as an integrated system of interacting components. Its goal would be to obtain "a scientific understanding of the entire Earth system on a global scale."[9] The emergence of a science of the Earth *system*, moreover, offered a promise of knowledge that would be valuable to decision makers addressing global habitability.

Prominent in the ESSC documents was a recommendation for an Earth Observing System to provide long-term global observations, with an emphasis on the long-term continuity of observations, both satellite and in situ. The importance of long-term records reflected the audience for these reports and portended a multiagency endeavor: the recommendations were made to several concerned agencies—to the National Oceanic and Atmospheric Administration (NOAA) and the National Science Foundation (NSF)—in addition to the sponsoring agency, NASA.

Late 1986 brought the beginnings of a coordinated government response. NASA, NOAA, and NSF had been developing parallel global change programs, but in 1987 a joint letter from the three agencies to the director of the Office of Management and Budget (OMB) proposed the idea of a budget presentation coordinated across the agencies. From this point on, OMB was instrumental in developing the USGCRP. Later that year a consortium of eight agencies formed the federal interagency Committee on Earth Sciences (later the Committee on Earth and Environmental Sciences, now the Committee on Environment and Natural Resources). The first funding for the USGCRP per se came in fiscal year 1989, and the first related descriptive document that accompanied the president's budget was produced for the fiscal year 1990 submission. Joint submission of agency budgets was a novel concept, at least in the Earth sciences. The process produced new initiatives that were coordinated if not necessarily integrated. Thus, the USGCRP was initiated and first presented in the federal budget by President Reagan, was codified into law in 1990 (see Appendix A), and was implemented by President Bush; today it is being carried forward under President Clinton.

Scientific Roots of Global Climate Research

The intellectual crucible in which the USGCRP was formed, however, was itself forged far earlier. The possibility of global changes in the biological, physical, and chemical environment had been recognized in the nineteenth century and became a widely accepted idea by the beginning of the twentieth century. In 1957, Revelle and Suess[10] pointed out that most of the carbon dioxide emitted from fossil fuel combustion would remain in the atmosphere for many years and drew on emerging climate modeling capabilities to suggest possibly alarming impacts on climate. In the early 1960s two major international conferences, known by the acronyms SMIC and SCEP,[11] put the issue on the international agenda. At the same time, convincing observational evidence emerged that human activities were in fact changing the chemical composition of the global atmosphere. Measurements first taken by Charles David Keeling in 1957 revealed that carbon dioxide was indeed increasing in the atmosphere at the planetary scale. In 1964 the President's Science Advisory Council brought the issue to the attention of the U.S. government. Subsequently, beginning in the late 1960s, early computer model simulations started to explore the possible changes in temperature and precipitation that could occur from increasing human-induced emissions of greenhouse gases into the atmosphere.

During the 1970s and early 1980s, an important set of environmental topics was closely considered by the National Academy of Sciences (NAS). Foremost among these issues were potential changes in climate and losses in stratospheric ozone. The NAS convened several panels and committees under leading scientists such as the late Roger Revelle[12] and Jule Charney.[13] The resulting reports projected that energy production from fossil fuels would continue to increase atmospheric concentrations of carbon dioxide and estimated that a doubling of the atmosphere's carbon dioxide concentration could potentially raise global average temperature by 1.5 to 4.5°C (about 2.7 to 8°F) and produce a complex pattern of worldwide climate changes. Charney and his colleagues concluded that if carbon dioxide continued to increase there was "no reason to doubt that climate changes would result and no reason to believe that these changes would be negligible."[14] The Revelle group saw a clear need for two kinds of action in response: "organization of a comprehensive worldwide research program and new institutional arrangements." In the same period, ecologists also recognized that massive changes in ecosystems caused by land-use changes and other stresses could affect the carbon cycle. In this juncture of scientific findings, then, are the beginnings of the partnerships among the life and Earth sciences that have become the hallmark of global change science.

Still other studies addressed a widening range of potential global change impacts and their policy implications.[15] In 1979 and 1989 major World Climate Conferences[16] were convened by the World Meteorological Organization and other international bodies. International meetings[17] converged on the conclusion that the implications of changing climate should be assessed for development policy. In 1988 the Intergovernmental Panel on Climate Change, composed of hundreds of scientists from more than 50 countries, assumed responsibility for conducting periodic international assessments on climate change and its consequences. The latest of these[18] affirms the validity of scientific concerns and concludes that human influences on climate are becoming discernible.

Thus, throughout the past two decades the NAS/NRC and their international counterparts have continued to examine the science of climate change and variability and the associated policy implications for the United States and other nations. Additionally, the NAS/NRC have simultaneously considered climate change and variability within the broader context of global change. The CGCR, author of this report, and CGCR's predecessor, the Board on Global Change, have been charged with providing continuing guidance to national and international global change efforts. In 1995, CGCR undertook an initial assessment of the scientific programs of the USGCRP, reviewed the specific role of NASA's Mission to Planet Earth/Earth Observing System, and issued a report with recommendations (the "La Jolla" report)[19] and a follow-up report on the government response.[20] The present study significantly expands that effort.

Scientific Roots of Stratospheric Ozone Research

A related history of research concerns another pressing environmental issue—depletion of the stratospheric ozone layer that shields us from damaging ultraviolet radiation. In the early 1970s, proposals to build a fleet of supersonic transports raised questions about possible damage to the ozone layer from engine emissions in the stratosphere. A major U.S. research and assessment program was launched, and the NRC was commissioned to conduct a series of studies.[21] But soon Rowland and Molina[a] made the startling discovery that chlorofluorocarbons (CFCs), not airplanes, were the frightening threat to our ozone shield. Eventually, an international assessment was conducted under the auspices of the World Meteorological Organization and other international bodies.[22]

The discovery by Rowland and Molina reminds us that studies and reports often do not adequately address the complexities of the real world. Indeed, they can even significantly miss the mark. Studies of ozone depletion had focused on slow incremental changes and had sought incremental improvements through corresponding models and parametric analyses. Meanwhile, observations extending back to the 1950s had been tracking the amount of ozone over the Antarctic each year through its seasonal cycle. In the late 1970s an anomalous deficit was observed in the total amount of ozone over the southern hemisphere in late winter observations. Then in 1985 the British Antarctic Survey reported dramatic—and rapidly worsening—ozone losses in springtime ozone concentrations over Halley Bay.

Theories about the cause of this unprecedented and unexpected loss blossomed. Explanations ranged from the hypothesis of the simple redistribution of stratospheric ozone by atmospheric motion to proposed chemical reactions initi-

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[a] The Swedish Academy of Sciences awarded the 1995 Nobel Prize in Chemistry to F. Sherwood Rowland, Mario Molina, and Paul Crutzen for their work in atmospheric chemistry. Rowland and Molina published an article in *Nature* in 1974 that showed that CFC releases into the atmosphere cause stratospheric ozone depletion. Paul Crutzen had previously shown the importance of nitrogen oxide catalytic chain reactions in controlling the amounts of stratospheric ozone.

ated by the magnetic field focusing of solar electrons and protons. More complete information was clearly needed. In 1986, NASA began planning an airborne expedition using the ER-2 aircraft to penetrate the region of the stratosphere where ozone was disappearing. The mission, executed in August and September 1987 from Punta Arenas, Chile, demonstrated that ozone was being destroyed by chlorine and bromine radicals. The role of CFCs—molecules that transport chlorine to the stratosphere—in the destruction of Antarctic ozone was unequivocally confirmed. Shortly thereafter, laboratory and theoretical work pinned down other essential mechanisms of the process—mechanisms involving cloud particles, which had been overlooked in earlier studies.

With such overwhelming evidence in hand, the nations of the world moved with remarkable alacrity to mitigate the threat. International meetings developed strategies to control emissions of ozone-destroying substances, while the chemical industry worked to devise substitutes for CFCs. Within a few short years a comprehensive framework for controlling worldwide emissions had been put in place in the form of the justly admired Montreal Protocol.[23]

A number of lessons relevant to the broader field of global change research may be drawn from the case of research on Antarctic ozone depletion. The severity of the ozone phenomenon demonstrates that environmental changes are not always incremental or slight. Moreover, the severity of ozone loss came as a total surprise, even though the topic had been carefully considered by the scientific community. Finally, however, the problem was assessed in remarkably short order and effective remedial measures were rapidly instituted—*because a solid base of related scientific understanding had been developed through decades of focused observation and research.*

An additional critical point to make in this context is that many issues in global environmental change, such as climate change, are far more complex than even the difficult ozone story. The chemical, physical, and biological aspects of the greenhouse problem are extraordinarily daunting to study, and yet an additional and more difficult challenge probably lies in understanding the human dimensions of global change phenomena.

THE ROAD AHEAD

What surprises are in store in the future? By definition, surprises cannot be fully anticipated; at best they can be acknowledged as possibilities. As such they pose a special challenge to science. Science must formulate specific questions to set about obtaining the critical observations and performing the analyses needed to answer them. It is hard to ask questions that will anticipate all possible surprises *before* a surprise occurs.

Preparing science for surprise is, in part, the challenge that the CGCR faced in developing this report. Scientists believe strongly that unfocused research on the complex and varied Earth system is unlikely to be productive. On the other hand, scientists who view the world through pinholes are likely to bump into trees and fall off cliffs. How can needed focus be given to the USGCRP while still casting the research net sufficiently wide to catch the unexpected? In this report the CGCR has sought to define a *framework* for this endeavor, identifying a set of coherent domains of research that are likely to provide efficient and productive progress for science and to encompass the range of scientific and social issues implicit in global environmental change. This *framework* builds on the initial set of guiding principles defined by the committee in its La Jolla report and on the issues of great scientific and practical importance in mature areas of Earth system science that are identified in this report.

THE *PATHWAYS* FRAMEWORK

This report outlines a research framework across the wide scope of global environmental change in terms of the following primary topical areas:

- changes in the biology and biogeochemistry of ecosystems,
- changes in the climate system on seasonal-to-interannual timescales,
- changes in the climate system on decadal-to-century timescales,
- changes in the chemistry of the atmosphere,
- paleoclimate, and
- human dimensions of global environmental change.

Pathways begins with biology and biogeochemistry because of our intimate dependence on biological systems, because of the sensitivity of these systems to changes in the physical and chemical environments, and because of the pivotal role of biology in the changing biogeochemical cycles of the planet. These biogeochemical cycles are, in a sense, the metabolic chart for the planet; they provide particularly useful benchmarks of global change.

We look next into the climate system, focusing initially on climate variability on seasonal to interannual timescales and then on climate change on decadal-to-century timescales. We find that we also must consider climate variability and change on the intermediate timescale of a human generation.

Changes in the chemistry of the atmosphere drive many global changes; the atmosphere quickly transports chemical inputs from whatever source, and the chemical loadings are of sufficient scale that they can no longer be ignored. Testing ideas about global change on longer timescales is not like research to improve weather forecasts, in which feedback and correction are almost immediate. The paleoclimate record offers a unique opportunity to assess ideas about the dynamics and causes of global environmental change and variability. This record also tells us that large departures from simple expectations have occurred in the past, forcing the recognition that any program addressing global change must be sufficiently broad in scope to ensure that surprises are caught early. This consideration is particularly important for devising observational strategies.

The human dimensions of global environmental change—that is, humans and their institutions as both agents and recipients of change—are integrated where possible into the other topical chapters of this report and are also the subject of a separate treatment. Many concerns about the changing environment are tied directly to concerns about human and ecosystem health and welfare.

The discussion of each of the six primary topical areas is structured in terms of *Research Imperatives*—central issues posed to the corresponding scientific community by the challenge of global environmental change. Four to six Research Imperatives are identified for each topical area. Sometimes these imperatives closely interconnect. The Research Imperatives provide guideposts for the research "pathway."

Each Research Imperative is addressed by a set of *Scientific Questions*. The limbs of the research strategy begin to branch and spread. If *surprises* are in the wind, we hope that this broadly spreading canopy of topics, Research Imperatives, and Scientific Questions will catch the signal.

The Scientific Questions are posed at a level of detail from which an observational program, space-based and in situ, can be defined, refined, and realized. The observational strategy also consciously recognizes that surprises might well be in store. *For this and other scientific reasons, an essential requirement of the observational strategy is to establish long-term, scientifically valid, consistent records for global change studies.* It is fortunate that the paleoclimate community has provided extremely detailed histories of climate and environmental change that can underpin the instrumental records, establishing some basis for the assessment of future monitoring. Long-term monitoring is a central scientific challenge for global change research. It is also a difficult challenge to meet in a social environment that so often values or wants something new.

Observations are essential to test hypotheses from which models can be developed. Models are essential if prediction and synthesis are sought. Observations are useless, however, if the data are inaccessible to users (e.g., because of the problem of data recorded in "write-only" memory). Data systems have been a constant challenge to all scientific investigations; they are particularly problematic when large amounts of data are involved, as in global change studies. Fortunately, through a unique confluence of satellite and computer technology, science stands on the threshold of a greatly enhanced ability to exploit such masses of data and hence is well positioned to monitor and predict changes in the global climate and environment. Satellites orbiting the Earth can monitor changes in sea height, wind velocity, atmospheric water vapor, snow cover, and a wide variety of other parameters. Satellite data can be merged with ground-based measurement networks in a matter of minutes through a series of telecommunications satellites, microwave links, and fiber. Data derived from these sources serve as inputs to large computer-based models, which in turn provide predictions about future environmental trends and variability. The existing and future Internet and associated services give the USGCRP an opportunity to manage this stream of data successfully and at reasonable cost.

A data strategy is needed that emphasizes flexible and innovative systems—systems that are less costly than the current EOS core system, that appropriately reflect focused responsibility for data character, that provide open access to the scientific community and the public, and that rapidly track technological developments.

REVIEW OF THE USGCRP

As mandated in the legislation establishing the USGCRP (see Appendix A), the NRC has provided continuing oversight and review of the program (see References). Oversight has been the responsibility of a consortium of NRC groups, coordinated through the former Board on Global Change (now the Board on Sustainable Development and its Committee on Global Change Research, CGCR) and other predecessors. For example, the Climate Research Committee and its panels (operating under the NRC's Board on Atmospheric Sciences and Climate) have overseen climate-related elements of the USGCRP, with particular attention to international programs such as the Tropical Ocean-Global Atmosphere (TOGA) program. The NRC's Committee on the Human Dimensions of Global Change has carried out seminal studies to define social science aspects of the USGCRP. The CGCR and other NRC units receive regular updates on program status at their meetings. With participation by these and other NRC boards, committees, and panels, the CGCR carried out a comprehensive review of the program in the summer of 1995,[24] followed in 1996 by a review of government actions taken in response to the 1995 report.[25] In November 1996 the approach to the *Pathways* report was determined at a CGCR meeting, which for the first time convened representatives from each of the USGCRP agencies and chairpersons and staff of each NRC committee involved in global change research. The findings and recommendations of the present report are based on this continuing stream of review and assessment.

The central purposes of the USGCRP areas are as follows:

- to observe and document changes in the Earth system;
- to understand why these changes are occurring;
- to improve predictions of future global changes;
- to analyze the environmental, socioeconomic, and health consequences of global change; and
- to support state-of-the-science assessments of global environmental change issues.[26]

These "central purposes" of the USGCRP set a clear, appropriate, overarching vision for the Program. Moreover, during the past decade, the USGCRP has realized an impressive array of scientific accomplishments. Progress has been made in understanding the loss of stratospheric ozone, and amendments and adjustments to the Montreal Protocol have benefited from research flowing from the USGCRP. Ice cores have provided evidence of past changes in the Earth's environment, and human-induced environmental changes have been documented. There is a much better understanding, including the development of large-scale models, of the important roles of terrestrial and marine ecosystems in the overall carbon cycle, including knowledge of how such systems might shift under a changing climate. The success in providing predictive and useful information about El Niño-Southern Oscillation (ENSO) phenomena is a significant step in providing scientific information for natural resource management and for improving human welfare, and it offers encouragement that the broader issues of climate variability and human-induced climate change can also be successfully attacked. Finally, some accomplishments in observations are noteworthy. The precise measurements from space of sea surface height by the U.S.-French Topex-Poseidon mission have advanced our knowledge of sea surface change and ocean circulation. The Mission to Planet Earth Pathfinder datasets have advanced our insights across a wide array of global change issues.

The inherent challenges in achieving the central purposes of the USGCRP, however, will be ongoing; to ensure our well-being for the foreseeable future, it is essential to meet these challenges. They also set a formidable and difficult agenda for science, and this conclusion carries with it the need to do better. We must find ways of advancing the scientific attack on the problems of global environmental change more effectively. Fortunately, with 10 years of experience of successes and setbacks, we are in a far better position to meet the scientific challenges in the coming decade. There is, in fact, a rich body of information, in the form of lessons learned, to be gleaned from the past decade.

Lessons Learned

What are the lessons of the past 10 years? The reviews carried out over the Program's first decade have in fact identified a key set of "lessons learned"—attributes that the Program must maintain and precepts it must observe to achieve greater and needed successes in attacking the difficult issues of global environmental change.

Need for Programmatic Focus

Where research communities have been given resources based on collaboratively established priorities to implement critical activities, maintain and distribute datasets, and synthesize the information, rapid and impressive progress has been made. Such successes have occurred primarily within the framework of formal programs (e.g., the TOGA studies of El Niño and the Upper Atmosphere Research Program studies of ozone destruction that led to the Montreal Protocol) and sometimes through grassroots initiatives (e.g., carbon cycle modeling). Many global change projects are currently on a positive trajectory and success is likely. However, many critical global change questions are not receiving the level of support needed to make similar progress; the sum of support for the current "focused"[b] programs, according to the USGCRP specifications, represents an inadequate fraction of what is needed to accomplish its goals. For example, of the total fiscal year 1998 budget request for the USGCRP, 61 percent supports space-based observation programs and 39 percent supports scientific research.[27]

In part this problem has arisen because of disaggregation of the national effort across multiple agencies. The agencies have neither an enforceable mandate to cooperate in a manner necessary to be successful nor a system that requires accountability of expenditures. The Committee on Environment and Natural Resources (CENR) of the National Science and Technology Council (NSTC) was designed to improve the coordination of both the USGCRP agencies and the budget crosscuts with OMB in presenting a national program. Unfortunately, the management framework has not had the expected effect. The desired "virtual agency"[c] has been quite far from reality.

The fact that a principal component[d] of the nation's global ocean-carbon cycle research program fell victim to budget reductions during 1996 to 1997 at DOE and required a last-ditch ad hoc rescue by NOAA is a clear statement of *programmatic failure, not programmatic success*. The tradeoffs between carbon sources and sinks were considered issues of immense economic significance in the recent Kyoto climate negotiations. Better understanding of the carbon cycle will be of great value in the ongoing negotiations. On the positive side, there are new and encouraging signs of focus and priority emerging from the NSTC/CENR structure and process.

Need for Program Balance

It can also be argued that there is currently an imbalance within the program among its major components: observing systems, data systems, and research and

[b] A "focused" program is defined by the USGCRP as an agency program that was created specifically to address the stated goals of the USGCRP. The total USGCRP "focused" budget is the sum of the "focused" agency programs. At one time the USGCRP also designated "contributing" programs that "provide important support to the program objectives but were initiated for reasons other than the focused Program goal" (FY 1992, *Our Changing Planet*).

[c] "Virtual agency" refers to the USGCRP interagency body. See USGCRP (1997, p.ii).

[d] The planned data analysis component of the program.

> ". . . the following set of **fundamental principles** . . . should guide the development and implementation of the US Global Change Research Program in the future:
>
> • **Science** is the fundamental basis for the USGCRP and its component projects, and that fundamental basis is scientifically sound.
> • The **balance** of activities within the program must reflect evolving scientific priorities. . . .
> • Success in attaching the long-term scientific challenges of the USGCRP requires an **adequate and stable level of funding** that promotes management efficientcies, encourages rational resource allocation, and allows examination of key scientific questions requring a long-term approach . . . " NRC, 1995

analysis. For instance, in the fiscal year 1996 USGCRP budget breakout, *Our Changing Planet,*[28] of the $1.83 billion allotted to the global change program, $1.19 billion (65 percent) was allocated to "Observing the Earth System" ($845 million) and "Managing and Archiving Data and Information" ($343 million). Of the remainder, $434 million was allocated to "Understanding Global Change" (24 percent). As indicated above, this distribution of resources essentially continued in the fiscal year 1998 budget. It can be argued that the large investment required to develop and deploy the space observation component of the USGCRP has comprised perhaps too large a fraction of the program's "focused" budget. Nevertheless, the space missions designed to facilitate global change research, such as sea surface altimetry and scatterometry and the Upper Atmosphere Research Satellite, have been great successes. Moreover, after an 11-year hiatus, the capability to obtain ocean color data has recently been restored with great scientific reward.

NASA's Earth Observing System (EOS) polar platforms—EOS AM-1, EOS PM-1, and EOS CHEM-1—were conceived as broadly scoped data-gathering systems. This foundation will be central for needed future missions and will set the baseline for a long-term operational environmental monitoring program that must be built on the operational weather and ozone-observing system of NOAA, the U.S. Department of Defense (DOD), and their international partners. However, while the EOS should begin to pay dividends with the scheduled 1998 launch of the AM-1 observatory followed by the late 2000 launch of the PM-1 mission, the initial focus of the USGCRP on EOS set a near-term timescale (and a cost) that made rapid response to scientific and technical challenges difficult.

The question of balance is further complicated by the realities of federal funding. Savings that might be obtained by trimming costs at NASA from space-based observations would be unlikely to flow within the agency to in situ observational activities, let alone to the research and analysis (R&A) component (or even to other space-based missions). Still more unlikely is the transfer of such funds to other agencies within the USGCRP. These are political and institutional realities. Nevertheless, there remains the question of balance within the overall

USGCRP observational system between space-based and in situ systems. (In fiscal year 1996 only 11 percent of USGCRP observations were devoted to in situ measurements.) Finally, although major breakthroughs have emerged from the R&A component of the national effort, *it is just this part of the effort that continues to receive serious cuts within several agencies in the USGCRP.*

Several lessons about Program balance can thus be extracted from the past 10 years. First, space-based observations are essential yet costly. We need to find ways to lower their cost while also making the space-based systems more budgetarily robust and flexible. We applaud NASA's Earth System Science Pathfinders and its rethinking of the EOS mission structure as steps in the right direction. Still another lesson is that in situ observations are critical (e.g., the TOGA ocean buoy array for ENSO prediction); yet in situ observational systems such as radiosonde and ozone networks continue to degrade around the world. We need to find ways to implement new in situ observing systems while restoring and maintaining key existing systems. Finally, in recent years the scientific community has gone through a difficult experience: R&A budgets in critical areas have continued to decline, and science is simultaneously being asked for answers to increasingly difficult and important questions. We must find ways to reverse this declining trend (NSF's proposed fiscal year 1999 budget is a welcome change).

Need to Maintain Critical Observations

During the past 10 years, the value of critical combinations of models and observations has been repeatedly demonstrated in providing the nation and the world with critical information about specific issues of global environmental change. The observing system that proved so valuable in the early detection of the 1997 to 1998 El Niño is a case in point. The research-based observing system and coupled atmosphere-ocean models developed under the auspices of the TOGA program to study ENSO phenomena made it possible as early as spring 1997 to detect and predict the 1997 to 1998 El Niño and its potential magnitude. Many social and economic systems are profoundly affected by weather events and climate patterns linked to ENSO; people in locations as distant as central Africa, southeast Asia, Australia, and North America are all benefiting from this scientific work, as agricultural, flood management, relief assistance, and market practices are adjusted.

Establishing an operational capability to maintain this initial ENSO observing system and training practitioners in the use of the data are large challenges, but there can no longer be any doubt that the investment has brought results of scientific interest as well as practical concern for natural resource management. This is an example of a crucial tenet of the Earth System Sciences Committee's strategy for studying global change: the institutionalization of critical measurement systems in an operational mode once their efficacy in documenting information valuable to policy makers is demonstrated in the course of a research program. This requirement will continue to be challenging for ENSO research, but more broadly the past 10 years have shown clearly that correctly transferring other key aspects of the observing program for USGCRP to operational programs will be very difficult.

This lesson also emerges clearly from negotiations on the polar platforms of NASA, NOAA, and DOD over the past 10 years. To date, the process is not a story of success for the USGCRP. For example, regarding coordination of the next generation of NOAA/DOD operational polar platforms and NASA EOS AM-1 and PM-1 satellites, if current plans proceed, there will be a significant gap between the conclusion of the flight of EOS PM-1 and the first NPOESS-1 (nominally planned for an afternoon crossing).[e] This gap will be significant because it will make coordination and calibration of the measurements taken by EOS PM-1 and NPOESS-1 extremely difficult.[f] Beyond this specific issue and the continuing problem of adequately sequencing observations, there is a more general lesson to be learned: it is difficult for an operational program (e.g., NPOESS) to incorporate an adequate level of scientific advice, review, and essential oversight to ensure that the scientific needs of global change science will be addressed. This difficulty has been exacerbated until quite recently by NASA's distance from the NPOESS planning process; moreover, NPOESS itself is driven by two operational agencies (NOAA and DOD) with somewhat different demands on the data and data calibration and accuracy requirements, and it is understandable (but problematic) that global change issues are not high on the priority list.

The connectivity between EOS AM-1 and the future midmorning operational polar platform, EUMETSAT's METOP-2/3, is even more confused. This general issue brings to mind the additional difficulty of ensuring adequate coordination internationally, as possibilities are explored to transfer scientifically motivated observations to operational programs.

Other examples of problems are beginning to arise as research programs dependent on global observations of ocean, land surface, and atmospheric properties are concluding their intensive field campaigns. No provision is in place to make the necessary commitments for systematic acquisition of operational climate and global change in situ data to continue the key time series started by these programs. These are precisely the types of problems that the USGCRP was charged to resolve.

Need for Well-Calibrated Observations

During the past 10 years, we have been reminded again and again of the painful consequences of attempting to use inadequately calibrated observations

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[e] The next generation of weather satellites is referred to as the National Polar-Orbiting Operational Environmental Satellite System (NPOESS).

[f] This is discussed further in Chapter 8.

to answer important questions about global environmental change. On a more positive note, great scientific advancements have been made when it is possible to use long-term, highly calibrated, rigorously maintained scientific observations. For example, precise measurements of atmospheric concentrations of carbon dioxide have yielded valuable information about the annual cycle of the biosphere and the distribution of carbon dioxide sources and sinks. Precise measurements of CFCs have also enabled the tracing of atmospheric and oceanic circulations and improved our understanding of stratospheric ozone loss. Precise measurements of solar radiance have helped us distinguish between natural and human influences on global mean temperature. The general lesson here, then, is that high-quality data are an immensely powerful lever to obtain scientific insights on global change.

Need for a Focused Scientific Strategy

The NRC's reviews of the USGCRP over the past decade (see References), notably the intensive community-based review conducted at La Jolla in the summer of 1995,[29] have consistently emphasized the need for the program to focus on critical scientific issues and the unresolved questions that are most relevant to pressing national policy issues. This document strongly reiterates that view. The nation and the world are beginning to make momentous decisions about development, technology, and the environment; at the same time, economic and political factors place severe constraints on budgets for research and infrastructure. A sharp focus on the truly essential investments in research and supporting infrastructure is thus more important than ever. **A more sharply focused scientific strategy for the USGCRP is urgently required.**

Charting and understanding the course of change in the Earth's physical, chemical, and biological systems, and their connections with human activities, are fundamental to the nation's welfare in the coming decades. Economic decisions, international negotiations, preservation of public health, and educational development demand this understanding. For example, without trusted knowledge about changes in the carbon and hydrological cycles, ecological systems, temperature structure, storm systems, ultraviolet intensity, nutrient deposition, and oxidant patterns, defensible positions for international measures to protect the environment cannot be established and sustained.

Development of this urgently required knowledge will demand concerted efforts and continuing *scientific leadership*. As the world's leading scientific nation, the United States, working with the international community, must recognize the importance of providing scientific leadership in defining and diagnosing changes in the state of the Earth system in the context of national needs and scientific interests. Strategic decisions on scientific goals, research programs, and supporting infrastructure are critical elements of this leadership, *and it is the committee's view that a new strategic approach is needed.* We thus present our findings and recommendations here with the full sense of responsibility that accompanies the strong belief that the challenges posed to people by global environmental change will not go away. The challenges will not be legislated out of existence; they will be faced by our children's children, and they must be faced by us.

NOTES

1. WMO (1979).
2. DOE (1977, 1980).
3. Goody (1982).
4. NRC (1966), Fein et al. (1983).
5. There have been dozens of NRC reports addressing this topic; the References contain many examples.
6. ESSC (1986, 1988).
7. Goody (1982).
8. NRC (1986).
9. ESSC (1986, 1988).
10. Revelle and Suess (1957).
11. MIT (1970, 1971).
12. NRC (1982a).
13. NRC (1979).
14. Ibid.
15. NRC (1982b, 1991).
16. WMO (1979, 1990).
17. WMO (1984, 1986).
18. IPCC (1995).
19. NRC (1995).
20. NRC (1996).
21. For example, NRC (1982c).
22. A recent update is contained in UNEP (1994).
23. Montreal Protocol to the Vienna Convention on Substances that Deplete the Ozone Layer (1987).
24. NRC (1995).
25. NRC (1996).
26. USGCRP (1997, p. 3).
27. Ibid., p. 78.
28. USGCRP (1995, p. 109).
29. NRC (1995).

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2

Changes to the Biology and Biochemistry of Ecosystems

SUMMARY

The study of large-scale ecosystems has become a rapidly maturing field of science. With the impetus of global change research, such studies have shown major successes over the past decade. Improved fundamental understanding of marine and terrestrial ecosystems and hydrology has already led to practical applications in weather and climate modeling, air quality, and better management and natural hazards responses for water, forest, fisheries, and rangeland resources. The development of spatially resolved global-scale ecosystem models has occurred only during the past five years. Computing capability and remote sensing technology have further driven change in the nature of the field. The capability has emerged not only to model at global scales but also to exploit data at these scales. Models have been developed and rejected based on the use of such data. Historically, large-scale ecosystem studies have also been integrative and multidisciplinary, with problems often worked from beginning to end with significant interactions with the human dimension components. Some of this experience stems from applied roots in the field and traditional links with agricultural, forestry, and fisheries issues, as well as environmental policy and assessment. In fact, as in atmospheric chemistry (see Chapter 5), there is a rich history of assessment at all spatial scales.

Areas of success in large-scale ecosystem studies include the following:

- Field and theoretical studies that have laid the foundation to understand the roles of vegetation and soils in weather and climate and that have advanced our methods for interpreting satellite data. Field experiments

planned for the Mississippi and Amazon River basins will complete this series of studies.

- Development of satellite observation techniques, ground-based observations, and models to determine changes in land cover type and spatial and seasonal changes of vegetation.
- Clarifying the role of nutrients in large-scale interactions of ecosystems with the atmosphere. The effects of nutrients such as nitrogen and phosphorus must now be systematically incorporated into global models of land-atmosphere interactions.
- Implementation of an ambitious program to measure and model the sources and sinks of CO_2 and trace gases from biological and biomass burning sources. This new information will facilitate the development of an observing system to determine trends and patterns of emissions and uptake at continental scales.
- Oceanic time series observations that have revealed previously unknown year-to-year variations in coupled ocean biology, chemistry, and physics, linked to climate variability.
- Regional ocean carbon studies that have quantified seasonal marine ecosystem effects on atmosphere-ocean CO_2 exchange, and El Niño-related variations in equatorial Pacific sources and sinks of CO_2.
- Modeling the impacts of climate change and variability on agricultural and forest ecosystems.

Overall, the U.S. Global Change Research Program (USGCRP) has been successful in advancing the science and tools required for space-based assessment of ecosystem change. The synergistic instrument complement consisting of the Earth Observing System (EOS) AM-1 and PM-1 platforms, combined with data from other ocean-sensing satellites, will largely satisfy the satellite data needs of the ecosystems community and will result in a massive improvement in the quality of remote observations. The ground- and ocean-based components of the program have had varying degrees of success. Atmospheric science components (biophysics and trace gases) have had the strongest programs. The more ecological components (vegetation and land cover) and integrative components (ecosystem manipulation experiments) have been supported on a rather ad hoc basis.

The *Research Imperatives* for the future are as follows:

- *Land surface and climate.* Understand the relationships between land surface processes and weather prediction and changing land cover and climate change.
- *Biogeochemistry.* Understand the changing global biogeochemical cycles of carbon and nitrogen.
- *Multiple stresses.* Understand the responses of ecosystems to multiple stresses.

- *Biodiversity.* Understand the relationship between changing biological diversity and ecosystem function.

INTRODUCTION

The ecosystems of the world are critical foundations of human society. People depend on ecosystems extensively for goods and services. Ecosystems provide such commodities as food, construction materials, and pharmaceuticals. In the context of global change, humanity's dependence on the biosphere for climate regulation, air quality, and clean water has also become starkly apparent. Thus, research on ecosystems in global change plays a dual role. First, decisions relating to climate variability, climate change, and other environmental problems require that we understand the impacts of climate, air pollution, and changing ultraviolet radiation on forests, agriculture, livestock, water resources, fisheries, biological diversity, and other critical life support systems. "Impacts research" builds on the foundation of basic and applied research in agronomy and soil science, forest science, fisheries, ecology, and other well-established disciplines, in a context increasingly influenced by new concerns (climate change, tropospheric pollution, ultraviolet-B). An ambitious effort is under way to conduct a U.S. national assessment of the potential consequences of climate variability and change to provide a detailed understanding of the consequences of climate change for the nation, including the interactive effects of environmental changes to climate, atmospheric chemistry, sea level, water quality, and land use. This chapter describes the research that is under way to provide appropriate links to that activity by emphasizing the scientific aspects of managed ecosystems, especially at the regional scale.

Second, managing global change must also recognize the role that ecosystems play in modifying the atmosphere and hence the ocean-atmosphere-land *climate system*. We now know that vegetation and soils influence climate by controlling the amount of radiation reflected or absorbed, the evaporation of water, and other direct feedbacks to temperature, precipitation, and weather systems. Terrestrial ecosystems store a great deal of carbon and influence atmospheric CO_2 both by releasing carbon as a result of land use (such as deforestation and agriculture) and by taking up carbon (the so-called missing sink). Marine ecosystems also influence oceanic carbon storage, interacting with physical and chemical processes. Ecosystems are also potent sources and sinks of other trace gases such as methane and nitrous oxide. Climate cannot be viewed as a force external to ecosystems: ecosystems participate in the shaping of weather, climate, atmospheric composition, and climate change.

This view of ecosystems, as both responding to and controlling environmental change, is one of the great intellectual and practical contributions of global change research. It has implications for a wide range of issues, from the improvement of weather forecasts (by taking into account the state of vegetation) to decisions about whether fossil fuel emissions should be limited and by how much.

Ecology contributes a unique perspective to global change research. While the geophysical sciences begin conceptually with a unified physical-chemical view of systems (based in fluid dynamics, thermodynamics, and photochemistry), the underlying paradigm of ecology emphasizes the diversity of ecosystems, resulting from the evolutionary history of organisms, and the soils and landforms or water bodies they inhabit. This perspective, of seeking understanding from the similarities and differences of processes across a range of environments, has become important in interdisciplinary Earth system research.

Planning the Program

At the outset of global change research, ecology as a discipline emphasized organism- to local-scale investigations, and the field's ability to address problems at even the landscape scale was limited. In addition, collaborations between ecologists, climatologists, and atmospheric chemists only began in the early 1980s. As a result, when the USGCRP and International Geosphere-Biosphere Program (IGBP) began, there was a substantial effort to develop the intellectual infrastructure within ecology to tackle problems at the global scale. A series of National Research Council (NRC) reports on global change and the IGBP planning process paid substantial attention to large-scale ecological issues, and the community also organized many important workshops and meetings. As a result, ecology has become much better prepared to take on science issues at scales from landscape to global on a breadth of issues and using tools not imagined a decade and a half ago.

Some issues have remained over that period. The focus on both ecosystem feedbacks and ecosystem impacts has been consistent in NRC and IGBP guidance throughout this period. However, as the science has evolved, the specific Research Imperatives have evolved substantially. It is worthwhile to review NRC guidance on global change and ecological research. For example, in a 1986 report[1] the summary recommendation (given with reference to the IGBP) was that "the initial priority . . . is to obtain additional experimental data, so that new models can be developed to extrapolate ecological responses to environmental changes that have not been experienced in the past." That report called for "laboratory and field experiments at the organism level and compilation of existing data on population and community patterns." It also observed that "experiments are needed on intact ecosystems, using large-scale manipulations" and that "in the long-term, ecosystem models must be assembled that couple population-community models with process-functional models."

This agenda had a major influence on the approaches taken by ecologists for both marine and terrestrial ecosystems, and all three of the NRC's recommended agenda areas were pursued in parallel by the community. In addition, long-term and large-scale observational (as opposed to manipulative) studies became a major component of research, both building on the foundation of the National Science Foundation's (NSF) Long-Term Ecological Research (LTER) program and arising from the increasingly fruitful collaboration with the Earth sciences community (in which observational campaigns play a larger role than in the largely experimental discipline of ecology). By the 1990s the research agenda had come into sharper focus. In 1994 an NRC report, the "Chapin report"[2] on terrestrial ecosystem research listed six major research areas:

- the interactive effects of CO_2, climate, and biogeochemistry;
- factors that control trace gas fluxes;
- scenarios for managed and unmanaged ecosystems;
- how global change will influence biodiversity;
- how global change will affect biotic interactions with the hydrological cycle; and
- how global change will affect the transport of water, nutrients, and materials from land to freshwater and coastal zones.

The Chapin report (NRC, 1994) also specifies the following needs:

- experiments that determine ecosystem responses to interactions among elevated CO_2, temperature, water, and nutrients;
- research to predict the role of landscape-scale processes, including land use; and
- research to determine how changes in species composition affect the functions of ecosystems, which is urgently needed and unlikely to proceed without focused attention.

Finally, the report lists as a major theme "the development and use of comprehensive models of ecological and physical systems" as a means of linking small-scale understanding to large-scale processes.

The NRC was not the only forum in which the role of ecosystems in global change was discussed. The late 1980s to early 1990s saw the rapid development of the IGBP Global Change and Terrestrial Ecosystems Core Project (GCTE) and the Joint Global Ocean Flux Study Core Project (JGOFS), addressing terrestrial and marine ecosystems, respectively. In addition, the International Global Atmospheric Chemistry (IGAC) program became involved in studying biological sources of trace gases,[3] the Biological Aspects of the Hydrological Cycle Core Project began activities in biophysical research, and the Scientific Committee on Problems of the Environment (SCOPE) organized several important collaborations on ecosystems and global change.[4] The IGBP elaborated considerably on the science agenda for global change research, and its deliberations have been documented in extensive reports. The IGBP GCTE research plan is in many ways consistent with priorities enunciated in the Chapin report and earlier NRC documents, though it presents a substantially more detailed vision for studying managed (especially agricultural) ecosystems.

Critical Results and the Development of Large-Scale Ecology

In view of this scientific vision, what were the critical results and advances in ecosystem research during the first decade of the USGCRP? The areas of progress have been diverse, and many critical advances have been highly interdisciplinary. Discussed below are some of the most important areas of progress.

Climate and Ecosystem Change: Evolution of Models and Observations

Techniques and datasets for inferring the behavior of ecosystems from large-scale observations evolved rapidly during the 1990s. The use of inverse modeling[a] to deduce spatial and, later, temporal patterns of terrestrial and oceanic CO_2 exchange produced a qualitative change in perceptions of the likely nature of terrestrial sinks. Although the use of inverse modeling began in the geophysical community, where both inverse modeling techniques and CO_2 global observations were developed,[5] collaborations to expand use of the technique rapidly grew to include ecologists.[6] Inverse modeling showed a sink of CO_2 in northern latitudes, through discrepancies between the observed interhemispheric gradient of CO_2 and the values predicted based on fossil emissions and characteristics of interhemispheric transport. Whereas initial analyses had reached different conclusions about the distribution of this sink between marine and terrestrial systems, later analyses using ^{13}C in CO_2 and measured O_2 indicated a substantial terrestrial sink (see Figure 2.1). This sink has been and remains difficult to quantify or even detect in forest and soil inventory measurements; atmospheric measurements remain the most conclusive evidence for the location of the so-called missing sink. Applications of the inverse methodology over time have also suggested correlations between climate and terrestrial CO_2 exchange at hemispheric to global scales. These observations remain preliminary but provide a foundation for future monitoring of global source and sink patterns.

The relationship of terrestrial carbon storage to climate is fundamental to understanding the interactions between climate and ecosystems that may occur during future climate changes. This subject has been addressed for terrestrial systems by a combination of experimental lab and field studies and by observational programs and data synthesis.[7] In addition, there has been vigorous model-

[a] Inverse modeling is defined as modeling where the chain of inference runs opposite the chain of causation: in the case of the carbon cycle, sources and sinks are modeled from atmospheric concentrations and transport.

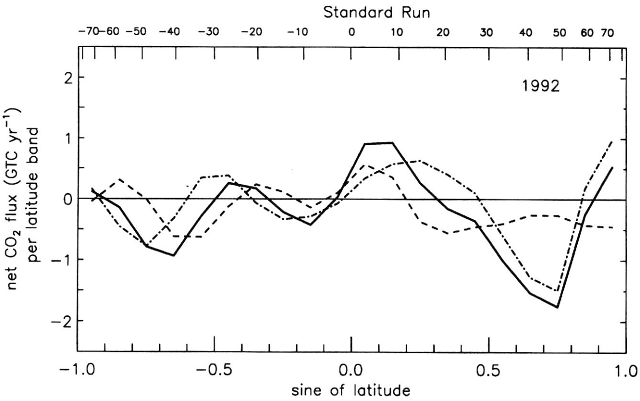


FIGURE 2.1 Latitudinal ocean/land partitioning of the sources and sinks of CO_2 versus latitude. The continuous line is the net flux of CO_2 after removal of fossil fuels. The dashed line is the net flux of CO_2 exchanged with the oceans. The dotted line is the net flux exchanged with land ecosystems. The sum of ocean and land fluxes equals the total net flux of CO_2. SOURCE: Ciais et al. (1995b). Courtesy of the American Geophysical Union.

ing of climate effects on both terrestrial and marine ecosystems.[8] Although the response of ecosystem processes to climate has long been of interest, recent work has led to a much more general understanding of temperature and moisture effects on biota and on the interactions of climate effects with internal ecosystem processes such as succession and the nitrogen cycle.[9] This work includes manipulative experiments[b] in the lab and field that have led to an improved understanding of microclimatic effects on biological processes and the specific behavior of particular ecosystems, whereas comparative studies and data syntheses have led to better understanding of ecosystem to global patterns. Long-term flux observations have illuminated the effects of climate on carbon storage: measurements over the past 25 years in the Arctic have shown tundra systems shifting from being a sink to a source of CO_2 as conditions became warmer and drier.[10] Recent advances in measurement techniques, especially the advent of eddy covariance techniques and their application in long-term studies, have produced unique data on climate effects on net ecosystem exchange (NEE).[11] Eddy covariance time series in forests have provided direct observations of the effects of unusually warm, cold, and dry conditions on carbon exchange.[12]

Because the temperature (T) responses of respiration (R) tend to be larger than those of photosynthesis (A) (T versus R is exponential, whereas T versus A

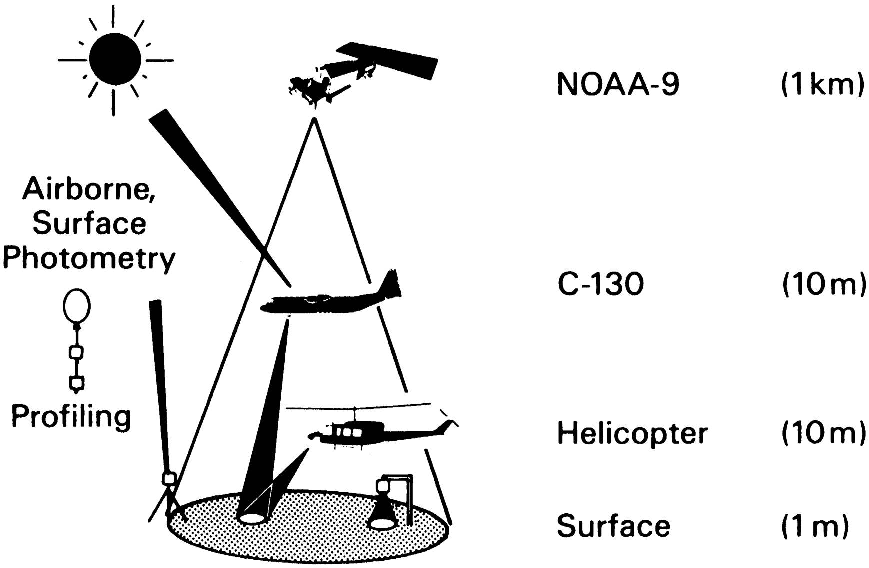
[b] Manipulative experiments are ones where some variable or variables are deliberately altered and the response of the system is observed (e.g., experiments with artificially elevated atmospheric CO_2).

is saturating), it has been hypothesized that global warming should lead to global net CO_2 emissions from ecosystems.[13] Recent studies using USGCRP global datasets have tentatively confirmed this hypothesis for short timescales (<1 year) while suggesting more complex interactions on interannual timescales.[14] Modeling studies have probed this type of relationship quantitatively, suggesting a dependence on rates of mortality, major effects in soils, interactions with the nitrogen cycle, and interactions between physiology and biogeography.[15] As observing techniques improve and time series lengthen, it has become increasingly possible to distinguish among alternative hypotheses about how future warming might affect ecosystems. An exciting development is the use of models to understand the emerging time series of climate and carbon exchange at the global scale.[16] Early efforts to model climate effects on ecosystems were extremely hypothetical.[17] The models used then had been tested at a limited array of sites, against "typical" or average conditions. The ability of the models to simulate the dynamic response of ecosystems to varying climate had in general not been examined. Currently, models used to project future ecosystem responses are being tested against observed dynamic changes resulting from interannual climate variations using data collected at local to global scales.[18]

Land Surface Processes and Climate

Research on the role of the land surface in climate has been a prominent area of research at the interface of ecology and atmospheric science over the past decade. It has led to dramatic developments in science and in observing systems. Beginning with a few provocative papers on the potential effects of land cover and inhomogeneities in land cover on climate, research on land surface processes has expanded to encompass a large and diverse theoretical and modeling effort validated by a series of highly successful international field campaigns.[19] The field campaigns have in turn led to a number of payoffs.

The use of eddy covariance flux measurements in ecological applications (in which measurement of the vertical winds and concentrations of a gas are measured together) was pioneered and verified in the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE),[20] and the datasets collected during FIFE remain a touchstone for validating land surface models. A key scaling principle for canopies was first combined with land surface models as a result of FIFE collaboration, greatly increasing the simplicity and success of canopy modeling (see Figure 2.2).[22] The validity of "vegetation index"-based estimates of surface conductance was tested against observations during FIFE, and this validation remains a cornerstone of the communities' confidence in satellite-driven land surface models. Results are just appearing from the Boreal Ecosystem-Atmosphere Study (BOREAS) campaign, which extended the FIFE paradigm to forested ecosystems. These results suggest a strong role for vegetation-atmosphere interactions in northern climates,[22] as do results from the



- **Simultaneous Radiometric Observations From All Altitudes, All Resolutions**
- **Coordinated Photometry and Radiosonde Profiling for Atmospheric Corrections**

FIGURE 2.2 Range of spatial scales addressed by the First ISLSCP Field Experiment (FIFE). SOURCE: Sellers et al. (1992). Courtesy of the American Geophysical Union.

NSF Arctic System Science program's Land-Atmosphere-Ice Interaction Study, and the importance of disturbance processes (such as large-scale fires) in land surface water and carbon exchange. They are also likely to make major contributions to understanding isotopic exchanges between ecosystems and the atmosphere.[23] Completion of the final planned experiment, the Brazilian-led Large-Scale Biosphere Experiment in the Amazon, will lead to a broad understanding of ecosystem-climate interactions in boreal, temperate, and tropical ecosystems. This work has had, and will continue to have, a major impact on our understanding of paleoclimate, contemporary weather and climate, weather forecasting, and climate projections.[24]

The need for comprehensive information on the land surface has also spawned a large effort to develop remote sensing algorithms for land surface variables. Major progress has been made in developing satellite algorithms to infer surface resistance to evaporation, temperature, soil moisture, and land cover.[25] Experience in using satellite data was gained using extant satellite systems such as the Thematic Mapper (TM), the Systeme Probatoire pour l'Observatión de la Terre (SPOT), and the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) systems. These data were successfully combined with algorithm development and evaluation in field campaigns such as FIFE, BOREAS, and the Hydrological and Atmospheric Pilot Experiment.[26] The intensive, decade-long effort in this area resulted in the experimental design of two major EOS satellites (AM-1 and PM-1) being optimized for synergistic measurements of land surface variables. The primary platform, AM-1, orbits with a morning overpass time, chosen to minimize cloud contamination for land surface imaging, and includes a synergistic combination of three instruments: the Moderate-Resolution Imaging Spectroradiometer (MODIS), the Multi-Angle Imaging Spectroradiometer (MISR), and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). MODIS has capability in the visible and near infrared for remote sensing of vegetation characteristics with high time resolution. MISR takes multiangle measurements that allow determination of albedo and better constrain so-called vegetation indices related to conductance to water and photosynthesis.[27] ASTER and LANDSAT provide high spatial resolution information on land cover. The proposed remote sensing strategy for the physical climate system and carbon cycle studies is shown in Figure 2.3.

Research on land surface processes exemplifies a constructive partnership among many groups: global climate modelers, organism- to ecosystem-oriented bio- and microclimatologists, ecologists, and remote sensing scientists, as well as geographers, plant physiologists, soil scientists, and hydrologists. Having defined the need for improved satellite algorithms early on, the community carried out the necessary theoretical, modeling, and empirical demonstrations of such a capability. These science requirements are now largely executed on the EOS AM-1 spacecraft. AM-1 is a large and expensive mission, but the community has confidence in the quality of its land surface mission. This forms one component of AM-1's full scientific agenda, which also includes cloud, aerosol, atmospheric chemistry, and oceanographic experiments.

Human Use and Modification of Ecosystems

At the beginning of carbon cycle research, the carbon cycle appeared to be roughly in balance, with fossil emissions balanced approximately by ocean uptake and atmospheric accumulation. Beginning in the 1970s, ecologists led by George Woodwell began to make the case that emissions from land use, largely deforestation, had to contribute significant inputs to the atmosphere. As this hypothesis became better and better documented, it became clear that to balance land-use emissions an additional sink process, dubbed the "missing sink," was required. The significance of land use in the carbon cycle was recognized prior to the USGCRP and the IGBP and has been a major focus of both programs since their

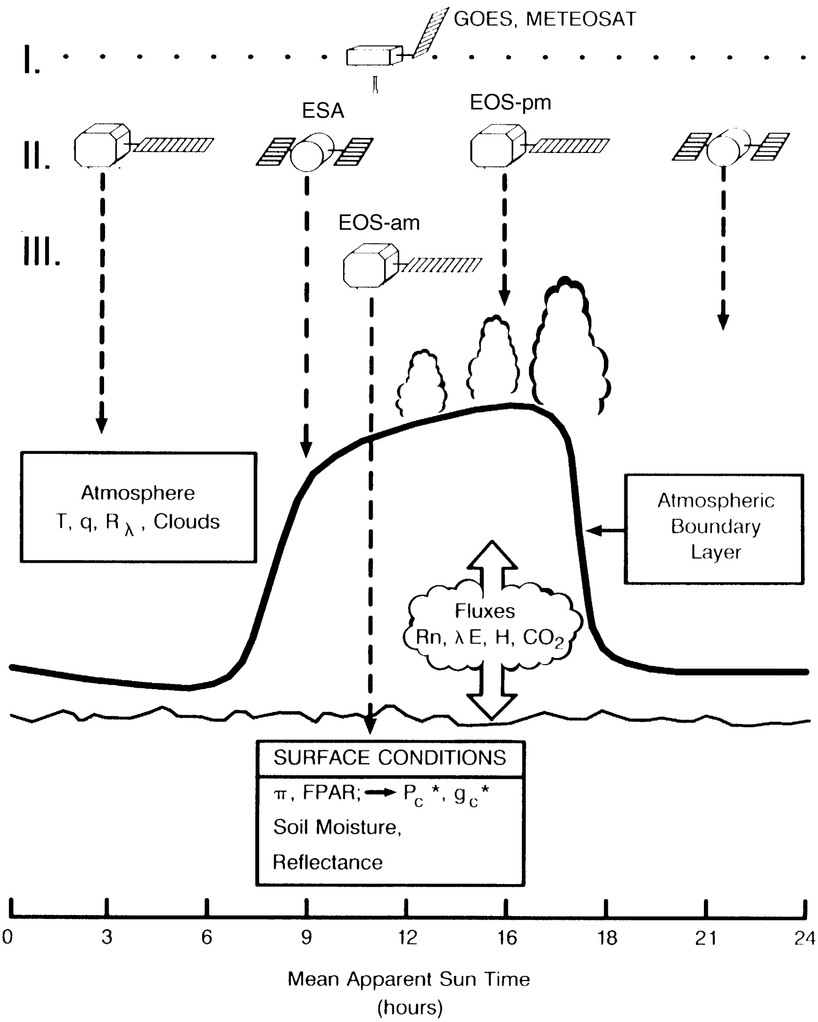


FIGURE 2.3 Satellite remote land-atmosphere interactions. Schematic of the diurnal variation of atmospheric boundary layer height and cloudiness for a humid continental region during the growing season; surface fluxes of net radiation sensible heat flux, water vapor, and CO_2 are depicted. The proposed remote sensing strategy is shown for the physical climate system and carbon cycle studies. I. Geosynchronous observations of cloud fields, reflectances, temperatures. (GOES, METEOSAT). II. Two polar platforms with sounding instruments and imagers capable of resolving cloud fields. Platforms are spaced in time to characterize diurnal variations of atmospheric variables (POEM-1, EOS-pm). III. Polar platform with surface imaging payload. A morning crossing time is preferred to minimize cloud contamination (EOS-am). SOURCE: Sellers and Schimel (1993). Courtesy of Elsevier Science-NL.

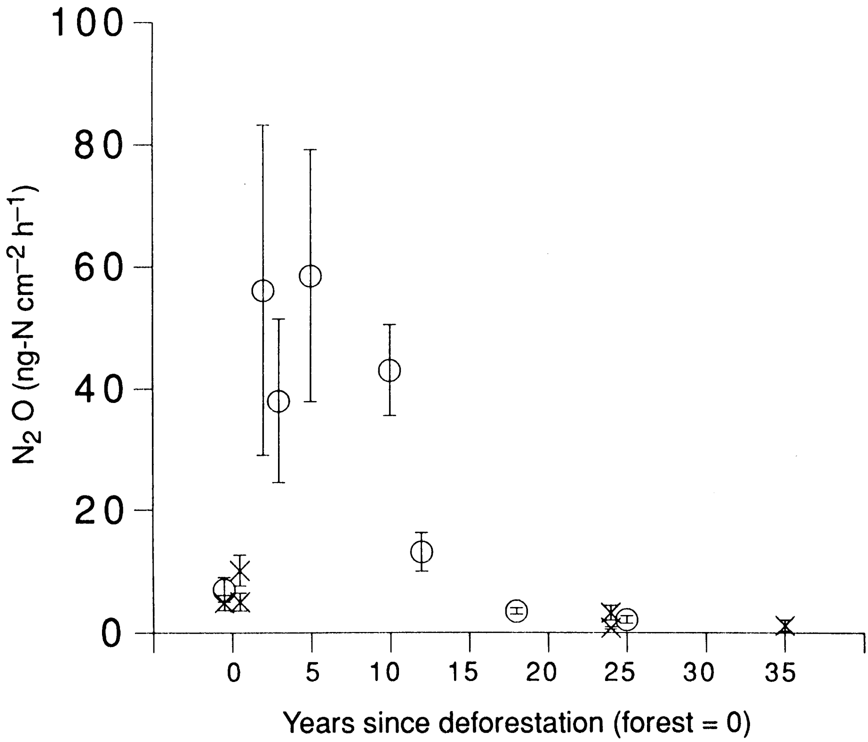


FIGURE 2.4 Average soil emissions (± 1 standard error) of N_2O plotted against pasture age (time since deforestation) for La Selva (C) and Guácimo (O). Forest sites are shown at 0 year. Significant differences were found among site means (analysis of variance, $p < .01$). SOURCE: Keller et al. (1993). Courtesy of Macmillan Magazines Ltd.

inception, as well as later in the International Human Dimensions Programme for Global Environmental Change. Whereas early attention was given to the carbon cycle, interest increased about the role of land use in altering trace gas budgets through soil processes and biomass burning[28] (see Figure 2.4). Indeed, it has long been clear that humans have exerted predominant control over many aspects of ecosystems globally.[29] The fragmentation of ecosystems owing to changing land use, with attendant effects on biotic and biogeochemical function, is another increasing concern central to the concern over the loss of biodiversity.

Research on land-use change has profited enormously from the availability of archived satellite data and improved techniques for satellite data analysis.[30] Early estimates of land-use change were based almost entirely on national statistics and inventory information.[31] Contemporary estimates are increasingly based on satellite information,[32] and techniques for continuing satellite monitoring into the future are improving. Commercialization of the TM and SPOT satellites and the accompanying expense of acquiring appropriate data over large areas set this effort back, perhaps by a decade. Today, computer technology is available to process large amounts of high-resolution data, but the satellite data remain costly. Retrieval of improved and spatially resolved historical land-use information is needed for retrospective analyses of the carbon cycle and to initialize models for global projections. Global retrieval remains a major problem, which is being addressed, albeit in a piecemeal and somewhat halting fashion at the present. However, understanding contemporary vegetation patterns, patterns of human land use, and the interactions of human and natural ecosystem processes is increasingly emerging as an important research area, and a vigorous community is developing.[33] This area of science has a strong natural link to biodiversity research since climate impacts on biodiversity will occur synergistically with other environmental changes.

Biotic Interactions and Global Change

Until recently, the term "global change" generally implied biophysical or biogeochemical change—to the extent that it implied biology at all. Changes in the biota were treated as resulting from changes in climate, CO_2, or land use. Climate and chemical changes have the potential to have significant impacts on biodiversity.[34] However, it has become evident that biotic changes in and of themselves can represent regionally and globally significant environmental changes. Perhaps the clearest example of such biotic change is biological invasion—the human-mediated transport of plants, animals, and microbes across Earth. The mobility of people and goods has increased the rate of movement of other species by orders of magnitude—and introduced species are now abundant over much of Earth, in coastal marine as well as terrestrial and freshwater ecosystems.[35] The result is homogenization of Earth's biota, with ubiquitous weedy species proliferating at the expense of local species.[36] More specific changes include many well-documented invasions that affect the health of humans and other species (most infectious diseases are invaders over most of their ranges). For example, introduced insect pests and microbial pathogens have done more to alter American forests[37] than climate change, elevated CO_2, and air pollution together—a statement that can safely be extrapolated for decades into the future. But biotic changes may interact with global change to alter biodiversity in hard-to-predict ways. Invading species also can affect the biogeochemical and biophysical properties of the invaded areas. Perhaps the best example is the widespread invasion of fire-tolerant African and Eurasian grasses into North and South America, Africa, Australia, and Oceania.[38] Where they invade, these grasses can increase fire frequency and thus affect regional biogeochemistry, simplify vegetation structure and alter biophysical properties of ecosystems, and interact strongly with other components of global change.

Invasion is not the only example of biotic change—human-caused removal of large predators, and sometimes even grazers, is widespread, and it profoundly alters the functioning of aquatic and terrestrial ecosystems.[39] Human actions also drive the extinction of species and genetically distinct populations. This is itself an irreversible change, and experimental studies are under way to assess linkages between functional diversity, the characteristics of organisms, and the functional responses of ecosystems to stress.[40]

System-Level and Long-Term Manipulations

Ecosystem responses to global change forcings include components that interact at a range of temporal and spatial scales, as well as subsequent feedback with the potential to amplify or suppress initial responses. This combination of numerous interactions, multiscale responses, and positive and negative feedbacks is a strong argument in favor of experimental studies on a scale that encompasses a much larger range of significant processes and interactions. Although recent progress in understanding feedbacks at the global to regional scale is still model-centered,[41] an increasing number of experimental studies complement modeling studies on whole-ecosystem responses to altered atmospheric CO_2, temperature, and water and nutrient inputs. Some of these studies have run or are scheduled to run long enough to provide information or potentially critical feedbacks that develop only as the forcing shapes biogeochemical and ecological phenomena over decades or longer.

These long-term ecosystem-scale experiments have already shown that the intensity of feedbacks and indirect responses can be surprisingly significant at a number of scales.[42] In Arctic tundra, altered nutrition under increased CO_2 led to homeostasis of net carbon exchange after only three years. Yet a 4°C temperature increase resulted in persistent carbon storage under elevated CO_2.[43] CO_2 enrichment under the more fertile conditions of the Chesapeake Bay wetlands leads to continued stimulation of photosynthesis and plant growth, especially below-ground growth, for at least nine years.[44] The contrast between the Arctic and saltmarsh studies shown in these examples suggests a key regulatory role for nutrient limitation; however, shorter-term experiments indicate no consistent modulation of CO_2 responses by nutrient availability.[45]

Soil warming could drive increased decomposition and mineralization, but it could also lead to increased drought and consequent decreases in primary production, decomposition, and mineralization. With nine years of summertime warming, Arctic tundra primary production changed only slightly, though the increased abundance of deciduous shrubs presages decreased decomposition and future declines in nutrient availability.[46] Warming in montane meadows also stimulated dramatic changes in plant species composition, with increased dominance by sagebrush, indicating likely future changes in carbon storage, nutrient cycling, and biodiversity.[47] Long-term nutrient additions can also stimulate dramatic changes in plant species composition. In Minnesota old fields, nitrogen additions simulating moderate to heavy atmospheric deposition led to the replacement of C_4 by C_3 grasses, with important decreases in carbon storage per unit of nutrients as well as changes in seasonality.[48]

Manipulative experiments have been important in marine as well as terrestrial systems.[49] In some oceanic ecosystems, supplies of major nutrients such as nitrogen and phosphorus persist throughout the growing season. In the late 1980s it was hypothesized that these regions might be iron limited.[50] Additions of iron in the equatorial Pacific, together with a tracer allowing the fertilized region to be tracked, increased phytoplankton and microbial activity, affecting both community composition and carbon cycling.[51] Experiments of this type, following both natural (e.g., atmospheric deposition events) and artificial fertilization experiments, with major as well as minor nutrients, have long been contemplated as prospects for ocean perturbation studies that can be followed with satellite ocean color data.

Multiple Stresses on Ecosystems

The dominant concern originally motivating global change research was global climate change. As ecologists and their colleagues from other disciplines began to address ecology at regional and larger scales, the importance of multiple large-scale environmental changes became apparent. Changes to climate, air quality, and land use may have synergistic effects, modifying the vulnerability of ecosystems to change. The concept of the metro-agro-plex, a region characterized by dense human populations, urbanization, and intensive agriculture, evolved in this context.[52] Examination of the geographies of regional air quality problems, urbanization, population growth, and intensive agriculture indicates that all are taking place in the same regions—for example, in Southeast Asia, the eastern and western seaboards of the United States, and Western Europe. These areas tend to have high air pollution levels, with elevated ozone, carbon monoxide, sulfur, and nitrogen. Urbanization and industrialization lead to air pollution and its precursor inputs, but the proximity of cities and agriculture makes the agricultural system vulnerable to damage from ozone, acidification, and other stresses. However, intensive agriculture is itself a source of trace gases to the atmosphere (NO, NH_3, and particulates) that may interact with regional air chemistry, particularly at the margins of the metro-agro-plex. Although air pollution is often thought of as an acute local or regional problem, metro-agro-plexes cover sufficient area and contain a high enough proportion of the world's population that they are properly thought of as a global problem.

Air pollution also has a direct global component. Recent work using observations and modeling has shown that nitrogen pollution has become a global problem and that likely future changes in fossil fuel and fertilizer use will lead to high nitrogen deposition worldwide.[53] Beginning in the 1980s,[54] anthropogenic nitrogen deposition has been considered to be a potential regulator of the carbon cycle. In the 1990s a number of careful studies[55] evaluated the potential effects of different forms of nitrogen deposition and concluded that global changes to the nitrogen cycle may have a serious impact on the global carbon cycle (see Plate 1). This analysis includes both deleterious effects in the core pollution areas and modest fertilizer effects in the margins of polluted airsheds.[56] It has also been shown, and is likely from first principles, that high N deposition is correlated with high ozone levels (because of the photochemical coupling of NO and O_3), leading to a potential multiple-stress situation combining the effects of N loading and oxidant stress.[57] This is of particular concern as these stresses, especially in deposition, are also implicated in changes to biodiversity.

Early experiments tend to support a "subsidy-stress" paradigm for N, in which N deposition can lead to increased growth up to a critical level, beyond which deleterious effects dominate.[58] The effects of previous land use may also play a major role in the vulnerability of systems to N stress, with the corresponding prior history of N budget changes and the physiology of current vegetation changing the quantitative relationships between N loading and ecosystem impacts.

CASE STUDIES

The Carbon Cycle

Ecosystem science has played a major role in studies of the carbon cycle. Although there remain substantial uncertainties about the carbon cycle and how it may behave in the future, significant advances have been made. Progress in this area is critical because carbon cycle research forms the basis for setting targets in international negotiations to mitigate climate change.[59] Understanding contemporary and possible future fluxes of carbon is the essential underpinning of sound policy to manage radiative forcing of the atmosphere. The development of accurate and reliable measurement techniques for carbon fluxes is a prerequisite for evaluating the success of measures undertaken to comply with the Framework Convention on Climate Change and to monitor international compliance with other treaty measures. Carbon cycle science is thus essential to international decision making.

By the late 1980s the budget of carbon dioxide in the atmosphere was obviously unbalanced (see Table 2.1). Carbon modeling suggested that fossil fuel and cement manufacture sources had essentially been balanced by ocean uptake and atmospheric accumulation.[60] However, beginning in the 1970s, ecologists increasingly found that substantial emissions were being made to the atmosphere from land-use change (in the 1980s these sources were largely tropical). The land-use contribution was based on estimates from carbon budgets for land conversion and area converted. Thus, even the definition of the complete set of terms in the carbon cycle (industrial, marine, atmospheric, and terrestrial) required

TABLE 2.1 Average Annual Budget of CO_2 Perturbations for 1980 to 1989

CO_2 sources	
(1) Emissions from fossil fuel combustion and cement production	5.5 ± 0.5
(2) Net emissions from changes in tropical land use	1.6 ± 1.0
(3) Total anthropogenic emissions [(1)+(2)]	7.1 ± 1.1
Partitioning among reservoirs	
(4) Storage in the atmosphere	3.2 ± 0.2
(5) Oceanic uptake	2.0 ± 0.8
(6) Uptake by northern hemisphere forest regrowth	0.5 ± 0.5
(7) CO_2 fertilization	1.0 ± 0.5
(8) N deposition	0.6 ± 0.3
(9) Residual (source)	(0.2 ± 2.0)

NOTE: Fluxes and reservoir changes of carbon expressed in Gt C/yr. Errors are accumulated by quadrature.

SOURCE: Schimel (1995). Courtesy of Blackwell Science.

reconciliation of oceanography, ecology, and geochemistry. The budgetary imbalance of 1 to 2 gigatons (Gt), or the inability of models to account for the fate of the excess carbon, is referred to as the "missing sink," and the excess carbon was assumed to be in terrestrial ecosystems because models of ocean uptake of CO_2 indicated actual uptake of 2 to 2.5 Gt, based on calibration against isotopic $^{14}CO_2$ (from thermonuclear bomb testing),[61] and fossil fuel emissions and atmospheric accumulation were known. This information set the stage for remarkable progress.

First, the missing sink, though widely assumed to arise from CO_2 fertilization of terrestrial ecosystems, had never been observed in any sense. The quantity was deduced by mass-balance difference, and the assignment of the cause to CO_2 fertilization was based on laboratory experiments and circumstantial evidence. Few suitable datasets existed to identify what was assumed to be a ubiquitous but spatially diffuse carbon accumulation in terrestrial ecosystems. In the late 1980s several groups began to estimate spatial patterns of CO_2 sources and sinks using inverse modeling (see Figure 2.5). Papers authored by atmospheric scientists, oceanographers, geochemists, and ecologists have explored this methodology and effectively established the existence of a CO_2 sink in northern hemisphere terrestrial ecosystems. The initial publications describing the northern hemisphere sink galvanized ecologists who had previously found the missing sink problem poorly posed for empirical research. Thus, the initial inverse work led to the initiation, modification, and reexamination of many studies.[62]

Work on the biological mechanisms underlying a terrestrial sink has also shown a remarkable and growing interdisciplinary character. The effect of CO_2 on photosynthesis, long known from laboratory studies, has been proposed as an explanation for additional ecological uptake of CO_2. Early work was largely

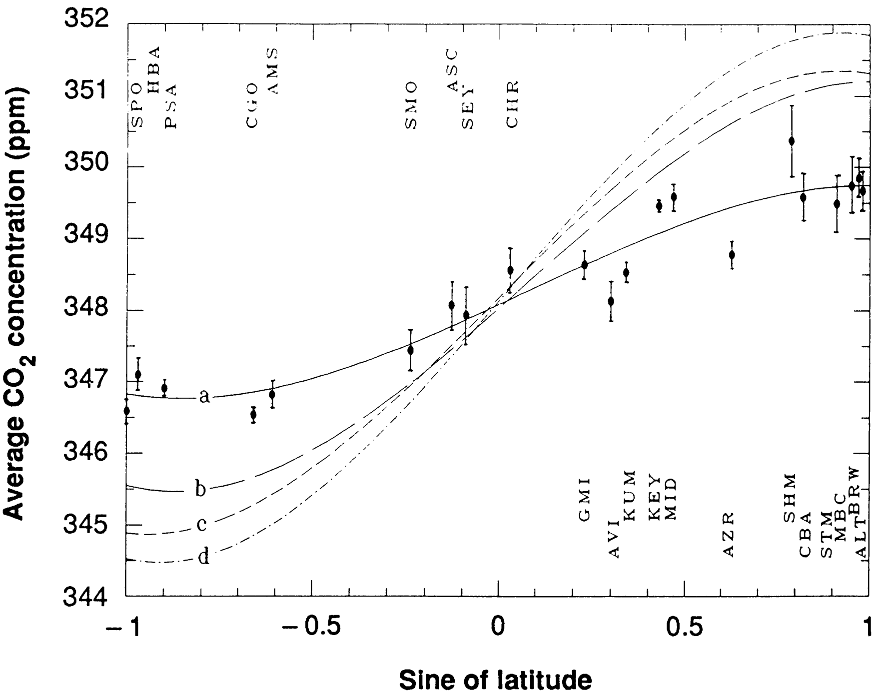


FIGURE 2.5 Observed atmospheric CO_2 concentrations at the sites of the NOAA/GMCC flask network. The error bars represent 1 SD of the annual averages at each site after adjustment to 1987. Curve (a) is a least-squares cubic polynomial fit to the data. The concentration distributions at the NOAA/GMCC sites have also been calculated with the NASA/GISS/General Circulation Model transport fields. Other curves are polynomial fits to the calculated CO_2 distributions (not shown) with fossil fuel emissions, seasonal vegetation (no net annual source or sink), tropical deforestation of 0.3 Gt of C per year, and three different cases of ocean uptake: (b) the compilation of CO_2 uptake based on the $-\Psi$ CO_2 data and empirical transfer coefficients; (c) CO_2 uptake based on the same $-\Psi$ CO_2 map but calculated with the Liss-Merivat relation for air-sea exchange; (d) an earlier estimate of ocean uptake totaling 2.6 Gt of C per year. SOURCE: Tans et al. (1990). Courtesy of the American Association for the Advancement of Science.

conducted by physiologically oriented ecologists and agronomists and focused on the effects of CO_2 on photosynthesis, secondarily on plant growth, and additionally on ecosystem consequences of enhanced CO_2 uptake. Although there was widespread skepticism that terrestrial productivity was limited by the availability of carbon—many ecologists believed carbon accumulation to be primarily nutrient limited—most early research focused on the initial physiological effects of increased CO_2.

In the mid-1990s the notion that the physiological effects of increasing CO_2 might be modulated by nitrogen availability became widely accepted.[63] The argument is that as organic matter accumulates in response to increasing CO_2 the associated nitrogen is sequestered from the actively cycling pool that supports plant growth.[64] As CO_2 fertilization progresses, the ability of plants and soils to store more carbon should become increasingly limited by nitrogen. Although this is difficult to test experimentally (because the effects of decades of environmental change on ecosystem nitrogen budgets is not understood or easily mimicked experimentally), its implications have been examined in a series of modeling exercises whose results have been compared to variations in the spatial and temporal patterns of observed CO_2.[65] Once again, these studies have included atmospheric transport modelers, geochemists, ecologists, and, increasingly, atmospheric chemists. This collection of interdisciplinary work has shown, first, that it is difficult to account for more than a fraction of the missing sink (30 to 70 percent) based on CO_2 fertilization alone, and, second, that changes in the seasonal cycle of CO_2 over the past decades are not consistent with CO_2 fertilization being the sole mechanism for the missing sink.[66]

With the new awareness that nutrients may control carbon cycling, several workers have shown that increasing anthropogenic nitrogen pollution could cause a substantial terrestrial sink of CO_2. The magnitude of this sink would depend on the spatial distribution of pollution, the fraction of areas where N pollution is serious enough to reduce productivity, and the fate of N in ecosystems.[67] The N-driven sink could account for some of the spatial and temporal differences between estimated terrestrial uptake and modeled CO_2 effects.

The past decade of carbon cycle research has yielded a panorama of extraordinary scientific accomplishment, and yet daunting challenges remain. Identifying source and sink regions, and the controls on these systems, is an extraordinarily difficult scientific problem. However, it is also a pivotal problem and must be attacked. This attack may require a more intensive and coordinated battle plan than the highly successful but ad hoc efforts of the past 10 years.

Modeling Ecosystems Across Multiple Levels of Biological Organization

Early models of terrestrial biogeochemistry lumped terrestrial biota into a small number of compartments, defined as living and dead and characterized by turnover times. Even major biomes were not always distinguished. The effects of changes in vegetation distribution (amply documented in the paleorecord) were not considered. The ways that ecosystem models deal with biota have changed substantially in the past decade. It is now widely recognized that functional differences between vegetation types influence ecosystem processes. It is also recognized that different vegetation types are used differently by humans. These differences to humans are not adequately indexed by net primary productivity (NPP); for example, many western U.S. rangelands have NPPs similar to montane forests, yet these systems are hardly interchangeable. Contemporary models incorporate a substantial amount of information on species or growth form attributes and simulate behavior that differs in the face of similar stresses depending on biotic and edaphic properties.[68] Although knowledge about the linkage of functional (carbon, water, and nutrient dynamics) to population-community processes is in its infancy at global scales, it is widely viewed as the next major challenge. One influential, if highly simplified paper, suggested that future changes to global ecosystem carbon storage will be dominated by the population processes of mortality, recruitment, and rates of migration or recovery.[69]

The importance of considering processes across biological levels of organization was highlighted by a recent large-scale international collaboration, the Vegetation and Ecosystem Modeling and Analysis Project.[70] VEMAP compared models of biogeochemistry and biogeography for the conterminous United States under current and general circulation model (GCM)-simulated future climates (current climate is defined operationally as the mean over the past few decades). The project covered three models of biogeochemistry and three models of biogeography (vegetation type distribution), developed by leading groups from the United States and Europe. The project was structured as a sensitivity analysis, using factorial combinations of climate (from three GCMs) and direct CO_2 effects (simulations were done at 350 and 700 parts per million by volume CO_2). Simulations of biogeochemistry (NPP, carbon storage, N turnover) with climate and CO_2 change were also conducted, using potential natural vegetation and vegetation distributions from the three biogeography models. VEMAP was motivated by the desire of several ecologists and funders to have state-of-the-art ecological modeling results for input to the 1995 Intergovernmental Panel on Climate Change (IPCC) report. VEMAP's initial phases were conducted on an accelerated schedule to permit publication of results prior to the IPCC's deadlines.

While there have been several intercomparison studies of ecosystem models,[71] VEMAP was unique in linking biogeochemical and biogeographic processes. VEMAP also contributed greatly to developing consistent input databases and modeling protocols, allowing for both validation of models and their rigorous comparisons. The VEMAP data group provided a "bioclimatology" of the domain, which included adjustment of the data to account for topographic effects of elevation and rain shadows and the complete suite of variables needed as input for biological models (temperature, rainfall, wind speed, radiation, and humidity). The suite of climate variables was interpolated to preserve physical consistency among variables (e.g., both sunny and rainy days are represented) and was provided at consistent monthly and daily time steps. The climate data were coregistered to a map of potential natural vegetation aggregated into classes consistent with all six models and to soil property information. The GCM climate scenarios were then provided as changes from the base climatology. The database thus provided a "level playing field" that allowed intermodel differences to emerge clearly. In most other intercomparison studies, differences in the input data used for different models has clouded interpretation of model-to-model differences.

The first VEMAP publications described the study and presented the key results on climate change impacts as input to the IPCC.[72] The authors reported that CO_2 increases alone (with no climate change) caused modest effects on NPP and carbon storage, with potential leaf-level effects of 30 to 40 percent on NPP in all models scaled back to less than 10 percent by ecosystem-level feedbacks via nitrogen cycling and water availability (see Table 2.2). Modeled responses to climate change and changing CO_2 together were usually larger but more variable than to CO_2 alone. The responses were amplified because warmer conditions accelerated the model's N cycles, reducing the N limitation of carbon accumulation that occurred under the simulations of doubled CO_2 alone. When biotic change was included by linking the projections of vegetation redistribution to the biogeochemical models, the effects grew larger yet and more variable, with some models showing effects of opposite sign, depending on the combination of climate scenario, vegetation scenario, and models used. While the models agreed on current-day stocks and fluxes, their responses to environmental change were variable. As additional environmental perturbations were added to the study, the between-model differences in carbon cycling increased. In the first experiment, responses to CO_2 increase alone were modeled; then CO_2 plus climate changes were examined. Finally, the effects of CO_2 and climate on vegetation distributions and the effects of all three factors (CO_2, climate, and biogeography) on carbon stocks and fluxes were evaluated. As these additional factors were added to the experiment, the differences in predictions between models increased. Despite this not unexpected result, all of the biogeochemical models showed that the nitrogen cycle influenced the sensitivity of the carbon cycle to CO_2 and climate.[73]

The paradox of VEMAP—that the models agreed on NPP and carbon storage under current conditions but simulated divergent behavior under altered conditions—led to a detailed analysis of model mechanisms.[74] The analysis showed that, while the models agreed on continental average NPP and carbon stocks (see Table 2.2), they disagreed on spatial patterns within vegetation types and, more fundamentally, predicted different relationships of NPP and decomposition to nutrient and biophysical controls.[75] The differing spatial sensitivity of NPP to water versus nutrient regulation was a clear predictor of response to changes in the modeled climate conditions. Models that had high sensitivity to evapotranspiration (and hence direct climate effects) relative to nutrient limitation behaved differently under altered climate conditions than models with the opposite sensitivity. The validation studies conducted so far provide clear information on why models differ and on the data and experiments needed to establish the correct mechanism.[76] Efforts to test the VEMAP models are being coordinated with U.S. and IGBP networks of CO_2 fertilization experiments and canopy flux studies.

The VEMAP intercomparison required the modeling groups to agree on a common age for forest stands to avoid having differences in stand age confound

TABLE 2.2 Results from VEMAP: Biogeochemical Consequences of Changing CO_2, Climate, and Vegetation Using Three Biogeochemical Models (Biome-BGC, Century, and TEM), shown with Vegetation Redistribution Simulated Using Three Biogeography Models (MAPSS, DOLY, and BIOME 2). SOURCE: Data from VEMAP Participants (1995)

	NPP* (Tg C)			Carbon storage (Gt C)			
	Biome-BGC	Century	TEM	Biome-BGC	Century	TEM	
Current climate and CO_2	3,772	3,125	3,225	118	116	108	Models in general agreement
Doubled CO_2 (% change from control)	+10.8	+5.0	+8.7	+6.5	+2.2	+8.5	Effects are downregulated relative to leaf level potentials
Climate change and CO_2 (3 scenarios; % change from control)	+1.7 to +20.2	+14.6 to +23.6	+24.6 to +26.5	–11 to 27.7	+5.9 to +7.2	+12.3 to +16.1	Effects are larger than CO_2 alone but more variable
With vegetation redistribution (3 scenarios of vegetation change; % change from control)	–0.7 to +21.1	+11.3 to +26.0	+27.0 to +39.7	–8.3 to 39.4	–1.8 to +20.4	0.0 to +32.3	Variability in sign and magnitude of effects increases; effects of changing vegetation and physiology are roughly equal

* Net primary productivity.

model sensitivities. For some of the models, simulating equilibrium conditions implies simulating mature stands, whereas in others standardization implies choosing a disturbance frequency and then presenting model results from a particular phase of the cycle. The consequences of the explicit or implicit handling of disturbance and demography were felt throughout the entire experiment. The assumptions about forest stand conditions affected estimated resource use, biomass turnover, and carbon stocks. The reduction in spatial heterogeneity associated with assuming a single stand age or disturbance regime for each cell within a biome was evident in model-data comparisons. The demographic, physiological, and plant community consequences of disturbance proved of first-order importance, even using the highly aggregated VEMAP-class models.[77]

Three key findings stand out:

- First, the biogeochemical consequences of plausible scenarios of vegetation redistribution in response to large-scale environmental changes are as large as the direct effects of climate on biogeochemistry.
- Second, there are large differences in resource use among species or functionally similar groups of species ("functional types"). Changes in ecosystem function per unit change in resources (water, energy, nutrients) that were caused directly or indirectly by global change may be quite discontinuous, as the biogeographic consequences of climate change interact with the biogeochemical changes. Thus, as species or functional types change in response to climate or other drivers of change, large changes in ecosystem function may occur because different plant species interact with the climate differently.
- Third, the direct and demographic effects of disturbance and succession have large effects on ecosystem processes at the continental scale. These effects are evident even in the VEMAP models where the processes of disturbance and succession are largely implicit. Present and future disturbance regimes (natural and anthropogenic) will have major effects on future ecosystems and must be included as a critical next step in ecosystem modeling. Such modeling of disturbances is currently a principal focus of the VEMAP group.

The VEMAP study represents a first step in introducing multiple levels of biological organization into large-scale ecosystem modeling. Other efforts are in progress within the IGCP-GCTE program and in numerous investigators' programs. By illustrating quantitatively the sensitivity of ecosystem function to biogeography—functional diversity among plant types, disturbance, and demography—the study emphasizes the importance of linking population/community-level ecology to biogeochemistry, a critical development for the eventual synthesis of global change and biodiversity research. VEMAP provides a partial template for how such integration of information and synthesis of ideas may occur. Key components are the intense and funded interactions of participants toward an ambitious but focused goal, support for development of the data infrastructure to meet the needs of diverse groups in a consistent fashion, and iteration of increasingly ambitious model experiments along with their rigorous comparison to data. Linking mechanistic models of population and community change to ecosystem function at large spatial scales is a more difficult endeavor but one that is within or just beyond the community's grasp. Finally, VEMAP provided valuable experience in modeling ecosystem responses across multiple levels of biological organization, even though the representations of population, successional, and demographic processes were empirical, simplistic, or implicit.

A RESEARCH AGENDA FOR THE NEXT DECADE

Introduction

The science agenda for ecology is in large part motivated by a series of questions about the effects of ecosystem change on the Earth system, the effects of climate on ecosystems, the consequences of direct human activities on ecosystems, and the feedbacks between climate forcing and ecosystems. Much of the early research on ecosystems and global change focused on the carbon cycle, biophysical effects of the land on the atmosphere, and biogenic sources and sinks of trace gases. Research in these areas must continue, but the questions for the next few years are more focused following a decade of progress. In addition, because questions continue to evolve as new discoveries are made, we attempt to characterize the process as moving from identifying a question to analyzing the resources, collaborations, and infrastructure required to address it. As ecology continues to evolve, techniques for combining individual creativity with highly coordinated resources and technology must likewise evolve.

Research Imperatives and Key Scientific Questions

The preceding discussion indicates there are four *Research Imperatives* that should guide ecosystem studies in the USGCRP for the coming decade:

- *Land surface and climate.* Understand the relationships between land surface processes and weather prediction, and changing land cover and climate change.
- *Biogeochemistry.* Understand the changing global biogeochemical cycles of carbon and nitrogen.
- *Multiple stresses.* Understand the responses of ecosystems to multiple stresses.
- *Biodiversity.* Understand the relationship between changing biological diversity and ecosystem function.

Land Surface and Climate Imperative

Ecosystem-atmosphere interactions that affect climate continue to be an important research topic. Land surface processes are key to understanding regional climate, regional climate change, and climate prediction.

- How do land surface biophysical processes interact with regional climate and modify patterns of interannual climate variability?
- How does including knowledge of the land surface state affect weather prediction and seasonal to interannual climate prediction?
- How might changing patterns of land use affect the climate of the future?
- How might large-scale atmosphere-ecosystem exchange of water and energy change in a high carbon dioxide world?

Biogeochemical Imperative

Research on biogeochemical cycles is fundamental to global change science. Research for the next decade must focus on the role of the terrestrial and marine biospheres in today's carbon cycle.

- How is terrestrial carbon storage regulated by land use, changes to marine ecosystems, internal ecosystem processes, and climate, and how might this storage change in response to future environmental changes?
- What are the consequences of the anthropogenically accelerated nitrogen cycle?
- Can we quantify the interactive roles of increasing CO_2, the changing nitrogen cycle, and land use in terms of present and future terrestrial carbon storage?
- How will the role of marine ecosystems change with future changes to ocean circulation, temperature, and nutrient/toxic inputs?

Trace gas biogeochemistry contributes to changing tropospheric chemistry, affecting radiatively active greenhouse gases. As research has progressed, the role of changing land use in changing trace gas emissions has come more sharply into focus. Other disturbances such as fire, pest/pathogen outbreaks, and biotic changes due to extinctions or invasions that may accompany changing land use should also be considered.

- What are the current budgets for the sources and sinks of biogenic greenhouse gases, especially methane and nitrous oxide?
- How is current environmental change, including land-use change, fertilization, and atmospheric N deposition, affecting the sources and sinks for these gases?

- How might the sources and sinks change in the future with changing land management, climate, and chemical inputs?
- As global use of anthropogenic nitrogen increases, is there potential for nitrous oxide emission or methane consumption to change rapidly?

Early work on biogenic trace gases focused on radiatively active trace species. Measurements made during the USGCRP and by IGBP projects have demonstrated that biogenic gases from microbes, plants, and biomass burning influence atmospheric photochemistry and aerosol formation, thereby impacting the atmospheric cycles of ozone, the hydroxyl radical, and reactive nitrogen. These projects have thus led to questions regarding reactive biogenic compounds, including aerosol precursors.[78]

- What changes are occurring to the atmosphere-ecosystem exchange of reactive trace gas species (nitric oxide, ammonia, nonmethane hydrocarbons, dimethyl sulfide)?
- What biological and pyrogenic processes control these exchanges, and how might they change in the future?
- What is the role of changing biogenic trace gas emissions in the changing photochemistry of the troposphere and stratosphere?
- Aerosols have become a major issue in climate. What roles do sulfur and organic compounds from biogenic sources, dust from agriculture and other soil disturbances, and biomass burning play in global aerosol forcing?

Multiple Stress Imperative

Work during the past decade has shown that climate and CO_2 interact and that changes to the global nitrogen cycle likely affect this interaction. In addition, the susceptibility of regions to climate and biogeochemical change is greatly modified by changes to land cover. Research on global climate change impacts at first emphasized the direct effects of CO_2 on climate but has increasingly emphasized interactions of CO_2 and climate with the nitrogen cycle as well as interactions with other stresses.[79] Research on climate effects on ecosystems should be conducted with the realization that climate change is only one of a number of simultaneous impacts in many systems.

For regional scales the focus is changing from single-factor stresses (e.g., ozone) to consideration of multiple impacts. In areas of dense human populations, where industry, urbanization, and agriculture coexist (the "metro-agro-plexes"), the interactive effects of environmental changes to climate, atmospheric chemistry, sea level, water quality, and land use may dominate, producing consequences different from those expected based on single-factor studies or models. The study of multiple stresses (such as changing climate, air pollution, or water quality) must come to the fore, and large-scale experimental studies (which today focus on, e.g., CO_2, soil warming, and ozone exposure) must address interactive effects.

- How do multiple global changes interact to produce ecosystem responses?
- What are the interactions of changing land use, climate, nutrient and toxic inputs, and hydrology on ecosystems and their ability to produce goods and services and to sustain biodiversity?

Systems subject to multiple stresses tend to be affected by a combination of large-scale factors (e.g., climate) and regionally unique factors (e.g., air or water pollution, invasive species). Regional studies can be important in studying ecosystems inasmuch as a higher level of physical, biological, and chemical detail can be obtained and modeled at this scale.[80] We must develop a methodology for understanding the implications of multiple environmental changes on interactive human-ecological-hydrological systems.

- What are the required datasets, theories, and models needed to understand regional coupling of physical and chemical climate, land use, and ecosystems?
- Can we develop the science needed to manage regional systems subject to multiple stresses to provide ecosystem goods and services while maintaining ecological integrity?

Early discussions of the role of ecosystems in global change focused on terrestrial and pelagic ecosystems. Since then it has become apparent that changes to terrestrial ecosystems caused by climate and land use can substantially alter transfers of material from terrestrial to freshwater systems and ultimately to coastal marine systems. These processes are only crudely quantified.[81]

- How do changes to climate and land use affect the transfer of water and materials between terrestrial and freshwater ecosystems?
- How does global environmental change affect the functioning of freshwater ecosystems?
- How do changes to terrestrial and hydrological systems alter coastal marine systems?
- How are coastal marine ecosystems changed by the interaction of climate, large-scale ocean circulation and biogeochemistry, and inputs from the land?

Biodiversity Imperative

As an ecosystem modeling framework has been developed for understanding biophysical and biogeochemical processes at regional to global scales, the interaction of ecosystem function with species ecology has emerged as a topic of increasing urgency. Although not all research on biological diversity lies within the global change research agenda, there is an important interface between the two areas. We must know the relationship of biological diversity to the functional diversity of plants, animals, and microbes. In addition, we must begin to understand the impacts of global change on biodiversity. The vulnerability of biodiversity to climate, nitrogen, and other anthropogenic changes will be conditional on other stresses (e.g., land-use change, toxics). Research on the impacts of global change on biodiversity must be conducted as part of an integrated program, ideally linking global change research to national and international biodiversity efforts such as DIVERSITAS.[c]

- How much functional redundancy exists in ecosystems?
- How does the functional diversity of organisms in ecosystems affect carbon uptake and sequestration, nutrient cycling, biophysical interactions with climate, and trace gas emissions?
- What information on plant, microbial, and animal function is needed to model the role of organisms in large-scale changes in community composition and ecosystem function?
- How will climate changes interact with other anthropogenic impacts to alter biodiversity?
- Are there critical (keystone) species governing large-scale ecosystem function, and can we identify what species could become keystone under changing environmental conditions?
- Can we identify either systems vulnerable to change as a consequence of biological invasion or species likely to be successful invaders?
- How might changes in pests and pathogens alter disturbance frequency, including land-use change?

Need for a Crosscutting Research Agenda

The discussion above frames the intellectual direction of global change research on ecosystems. However, experimental and modeling studies on ecosystems tend to be integrative, and many or most field studies will relate to many of the questions above. For example, the well-known long-term flux measurement program at the Harvard Forest, in Massachusetts, has provided insight into climate effects on ecosystem carbon storage and on the exchange of long- and short-lived trace species,[82] as well as a site for developing and testing new remote

[c] Established in 1991, DIVERSITAS is jointly sponsored by the International Council for Science (ICSU), by several ICSU bodies (the International Union of Biological Sciences, the International Union of Microbiological Societies, the Scientific Committee on Problems of the Environment, and the Global Change-Terrestrial Ecosystems Project of the IGBP) and by the United Nations Educational, Scientific, and Cultural Organization. The goals are to provide accurate information and predictive models of the status of biodiversity and sustainable use of the Earth's biotic resources and to build a worldwide capacity for the science of biodiversity.

sensing techniques. Soil warming studies have provided insights on carbon-cycle questions, trace gas questions (especially methane), the relative importance of physiological changes to species versus changes in species composition, and potential hydrological changes with global warming. Major field campaigns such as FIFE and BOREAS have provided information on a wide range of scientific problems and disciplines (from mesoscale meteorology to biodiversity). Because of this we describe the components of an ecological research agenda primarily by the type of research (the space and timescales addressed) or the level of ecological organization rather than by identifying research imperatives on an issue-by-issue-by-question basis. The elements of this research agenda (see Table 2.3) are described below.

Components of the Research Agenda

Observe Long-Term Trends and Interannual Variability in the Forcing and Responses of Ecosystems

Long-term measurements and experiments are a crucial component of ecological research, and, given the range of rates of ecosystem change (from seconds to millennia), many of these time series must span years to decades. As discussed later under "Lessons Learned", observational time series and long-term experi-

TABLE 2.3 Key Measurements and Research Imperatives: Need for a Crosscutting Research Agenda

Ecosystems And Physical Climate	Sources And Sinks Of Biogenic Gases	Multiple Stresses And Ecosystem Change	Biodiversity And Changing Ecosystem Function	Key Measurement
X	X	X	X	Network of sites.
X	X	X		Vegetation index/ocean color.
	X			Atmospheric composition.*
	X	X		Ocean pCO_2.
X	X	X	X	Land cover.†
	X	X	X	Toxic and nutrient deposition.
	X	X	X	Large-scale manipulation.

* Measurements of moderate to long-lived compounds from a global network (e.g., CO_2, $^{13}CO_2$, N_2O, $C^{18}O_2$, CH_4, CO, O_2).

† May be required at a range of spatial resolutions depending on the question.

ments have yielded many fruitful insights into ecosystem behavior that are relevant to global change. These achievements were possible because long time series allow small but consistent responses to be observed against a background of considerable variability.[83] Time series observations also allow the direct observation of system responses to trends and major climatic events.[84] It is imperative that the scope of time series observations and long-term experiments be strategically broadened. Critical areas for long-term studies include the following.

Experimental manipulations

While much of our understanding of long-term and global- to regional-scale feedbacks is based on models, long-term experimental studies are vital for discovering key interactions and for testing models. Studies of whole-ecosystem responses to altered atmospheric CO_2, temperature, and water and nutrient inputs are central to understanding the mechanisms through which environmental changes affect ecosystem processes. Some system-level manipulations have run or are scheduled to run long enough to provide access to potentially dominant feedbacks that develop only as the influence of the forcing penetrates biogeochemical and ecological compartments with time constants of decades or longer. Studies of mature forest stands, of CO_2 changes in concert with other changes, and of the effects of diversity remain high priorities. Experimental manipulations of disturbances (fire, insects, and human land use) are also potentially worthy of study. Equally important is the meta-experimental design, the choice of systems in which to conduct system-level manipulations, and the integration of responses across diverse types of ecosystems, as opposed to the specific manipulations performed at a site (the conventional experimental design).

Direct forcing of ecosystem change by human activities

Changes to climate and atmospheric composition are global. The ubiquitous nature of human resource use makes human impacts on ecosystems a globally distributed problem as well, although the specific impacts vary from region to region. Data on human impacts are often collected as a snapshot, but data on land use, pollution, and resource use should be available as time series. Many human impacts are cumulative, and analyses of land-use effects on terrestrial carbon storage show the need for time series data on human impacts.[85] In any program evaluating global changes to ecosystems, direct human impacts must play a central role.[86] Human use of ecosystems also alters their susceptibility to modification by climate and other "natural" processes.[87] Understanding ecosystem interactions with the physical environment requires knowing the type and state of ecosystems present, making knowledge of changing community composition and management imperative. The global distribution of human impacts over time must be known. Key datasets include the following:

- *Land cover.* The type and characteristics of global managed and natural vegetation must be known for the present, for the past (as best as can be determined), and from now forward (notably through monitoring, using high-resolution remote sensing). An historical record from the beginning of the industrial era is needed to assess the effects of land-use change on climate and the carbon cycle.
- *Land use.* The characteristics of land management, including agricultural practices, forest management practices, irrigation, urbanization, and other direct human manipulations of ecosystems need to be known (historically, to the extent possible) and monitored. This information is important for modeling ecosystems, trace gas emissions, and water quality.
- *Fisheries' practices.* It is becoming increasingly evident that fishing dramatically affects marine ecosystems and may alter their interactions with the marine physical environment. Marine ecosystem management practices must be documented as part of global marine ecosystem studies.
- *Atmospheric deposition.* Atmospheric deposition has recently emerged as a significant issue in global change research and for over a decade has been viewed as an important ecosystem stress at regional scales. Deposition of important anthropogenic chemical species, especially sulfur species, nitrogen species, and ozone, must be documented.

The above types of data, describing the impacts of humans on ecosystems in a geographic framework, form a central part of the information needed for large-scale investigations in marine and terrestrial ecosystems. They complement other datasets, such as those on climate, soil properties, ocean circulation patterns, and natural vegetation-type distributions that are already widely used in modeling.[88] Retrospective and contemporary data on human alterations and use of ecosystems and on collateral impacts are crucial not only for modeling the ecosystems affected but also because these data provide a critical link between ecological and human dimensions research (see Chapter 7).

Observations of atmospheric change

Time series observations of atmospheric CO_2 have long been a mainstay of global change research, and, as that time series has lengthened, the degree of insight it provides into the dynamics of the global carbon cycle has continued to increase. Time series measurements of other gases such as methane, nitrous oxide, and carbon monoxide and their isotopic composition are also crucial and have provided insights into their biogeochemistry.[89]

The current system of international observations emphasizes “background” atmospheric conditions, leading to better coverage of the relatively more uniform marine environments than their terrestrial counterparts. Additional continental stations are required both to improve the analyses’ ability to resolve terrestrial influences on atmospheric CO_2, CH_4, and other species with more precision and to allow better quantification of regional patterns of trace gas exchange. Whereas background stations can be located at sea level, the high variability of short to moderately long-lived gases (e.g., CO_2, CH_4, CO) in the lower troposphere over land makes surface observations difficult to interpret. The difficulty arises because trends, seasonality, and biological processes are confounded with the strong diurnal cycle and wind-direction-dependent influence of air pollution near the surface. Ideally, continental measurements should be made on aircraft or from very tall towers; in fact, transmission towers of 400 m or higher are now being used opportunistically[90] (see Figure 2.6). Continental measurements are best made as a gradient with height from a tower or aircraft. In addition to using the vertical sampling scheme, continental sites must be located to sample the range of ecosystems and human systems present. The experimental design of the full sampling approach is critical and must be carefully analyzed before an investment in data gathering is made.

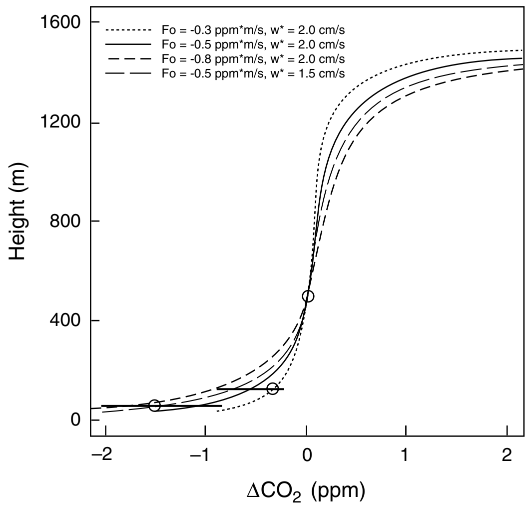


FIGURE 2.6 Vertical profile of CO_2 (difference from 496-m height) predicted for the convective boundary layer. The points show medians and the horizontal bars show the range of the lower and upper quartiles of the afternoon (1500 to 1700 EST) observations taken during June 1993. SOURCE: Bakwin et al. (1995). Courtesy of Munksgaard International Publishers.

Interannual variability and trends in atmosphere-ecosystem exchange

The new technologies of flux measurement by eddy covariance and relaxed eddy accumulation have made it possible to directly measure fluxes of water, CO_2, and many other species (e.g., ozone, nitric oxide, isoprene) above plant canopies. Simultaneous measurements of other properties, such as canopy nitrogen, link flux measurements to other ecosystem properties. It is imperative that a carefully designed network of long-term flux measurement sites be implemented.

On a larger scale, satellite measurements of vegetation activity have increasingly proven their utility for observing seasonal and interannual variations in vegetation activity.[91] Global observations of vegetation state are important to understanding climate-land surface interactions, biogeochemical cycles, and hydrology.[92] Although direct observations of canopy gas exchange provide information on ecosystem interactions with climate at local scales, remote observations of vegetation provide a spatial perspective. As the next generation of space-borne sensors and algorithms become available, with improved calibration and atmospheric correction, the detection of variability and secular trends will become more quantitative. Improved algorithms based on radiative transfer theory will allow retrievals of actual vegetation characteristics, as compared to the correlative approaches used today. Ground truth and calibration data for new algorithms must be collected in concert with site-based process studies (see below).

Measurements of ocean color (see Plate 2) as a proxy for phytoplankton biomass and the level of carbon dioxide in solution (partial pressure of CO_2 or pCO_2) provide information on marine biological activity and the potential for CO_2 exchange. Color and pCO_2 must be measured to determine their typical seasonal cycle and their responses to interannual climate variability. In situ calibration and validation data are required to fully exploit these data.

Terrestrial and marine ecosystem changes associated with global change

To interpret changes in atmospheric concentrations, fluxes, and surface energy budgets, the dynamics of vegetation and microbial communities must be known. Site-based multivariate measurement sets are required to understand these ecological processes. Plant and phytoplankton productivity (NPP) is a fundamental ecological variable that must be quantified to address a wide range of questions. In terrestrial systems the “allocation” of plant productivity among different plant parts is of fundamental importance. Although theory and experimental data suggest that allocation should respond to climate and other environmental changes, remarkably few observations exist to field validate the predictions of computer or laboratory models. Similar questions arise for marine systems regarding the distribution of NPP among phytoplankton species and trophic levels. Measurements of litter fall arising from leaf, wood, and root turnover, and of plant mortality are critical for understanding respiration, decomposition, and nutrient cycling. Litter fall, litter chemistry, litter decomposition rates, soil respiration, and nutrient availability are key ecosystem measurements needed to interpret and attribute causation to observed changes in fluxes and storage. In marine systems the export of particulate and dissolved organic matter below the euphotic zone is a primary variable. Measurements of NPP, respiration, and allocation, coupled with net CO_2 fluxes determined from eddy covariance, must all be components of an observing strategy for ecosystems under a changing global environment. Coupled measurements of controls over productivity, including climate variables, soil moisture, and nutrient availability, also will be of great value. In addition, as ecosystems change, their emissions of other trace gases may change. Long-term measurements of fluxes for N_2O, CH_4, dimethyl sulfide, and other trace species at a network of sites are required to detect changes in trace gas sources and to test process models of trace gas exchange. These measurements are particularly crucial in areas affected by intensifying human impacts (direct land use and changes to nutrient loading).

Summary: Key long-term studies

- Experimental manipulations of CO_2 and other environmental factors.
- Well-designed observations of atmospheric composition (CO_2 and its isotopes, CH_4, N_2O, O_2).
- Measurement of ocean pCO_2 (seasonal cycle and interannual changes).
- Satellite measurements of global ecosystems.
- Measurement of fluxes and ecosystem characteristics at a network of sites.

Regional Analyses, Extrapolation, and Observations at Multiple Scales

Both terrestrial and marine ecosystems possess spatial structure at scales from millimeter to global. Ecosystems also interact with the physical environment at a range of scales, from micrometeorological to large-scale circulation of the atmosphere and oceans. Because of the fine structure of ecosystems that is derived from the variability of organisms, patchiness in soil or water properties, and long time-scales of atmospheric processes, large-scale ecosystem studies cannot be applied in their entirety at the global scale.

Our understanding of ecosystem processes has been greatly increased by field projects that have explicitly sought to measure specific processes at multiple spatial scales. At the beginning of global change research on ecosystems, the community's ability to "scale up" or extrapolate process understanding of the organism or measurement plot to higher levels was rudimentary. Field projects organized to address this question, and the use of flux measurements and remote sensing, led to enormous progress in our knowledge of terrestrial ecosystems at large scales.

Regional-scale studies have been crucial in understanding the role of atmosphere-biosphere exchanges in tropospheric chemistry. Field campaigns such as the Arctic Boundary Layer Expedition series,[93] the Canadian Northern Wetlands Studies, and studies of biomass burning (South African Fire-Atmosphere Research Initiative and Transport and Chemistry near the Equator over the Atlantic) transformed our knowledge of tropospheric chemistry. Long-term regional monitoring for atmospheric deposition of acidic species and ozone is key to understanding the regional impacts of atmospheric change on ecosystems. Regional analyses should include both biophysical and biogeochemical interactions of ecosystems and the atmosphere. The biophysical and biogeochemical processes are naturally linked because biophysical processes are critical regulators of trace gas exchange and biogeochemical processes influence biophysical exchanges. Although site measurements of trace gas flux are useful for detecting change and testing models, regional measurements using atmospheric techniques are crucial for constructing budgets. Regional trace gas budgets are naturally estimated in multiscaled studies, such as the Large-Scale Biosphere-Atmosphere Project in Amazonia (see Figure 2.7), where the regional measurements may be tied to local process studies.

Remote sensing should be integral to multidisciplinary studies. Both terrestrial and oceanic remote sensing techniques provide high-resolution information, such as information on land cover (see Plate 3), relevant to regional processes. Integrated regional studies also provide an ideal venue for transferring knowledge about advanced remote sensing capabilities to new user communities, if the research is initiated by interdisciplinary teams.

Modeling at the regional scale is also essential to integrated regional studies.[94] As discussed earlier, it also provides an organizing framework and detailed information complementary to global models. Models provide an encapsulated, or planned, form of disciplinary knowledge in interdisciplinary investigations. The regional scale provides a venue where the critical processes in human-ecosystem-physical interactions may profitably be explored. Models designed for regional application can contain substantially more spatial and biological detail than global models (although this level of detail may only be available in certain regions).

Summary: Key regional measurements

- High-resolution mapping of land cover (for terrestrial systems) or of physical and optical properties (for aquatic and marine systems).
- Atmosphere-biosphere exchange of trace gases, toxics, and nutrients.
- Field programs measuring ecosystem fluxes at organism to regional scales.

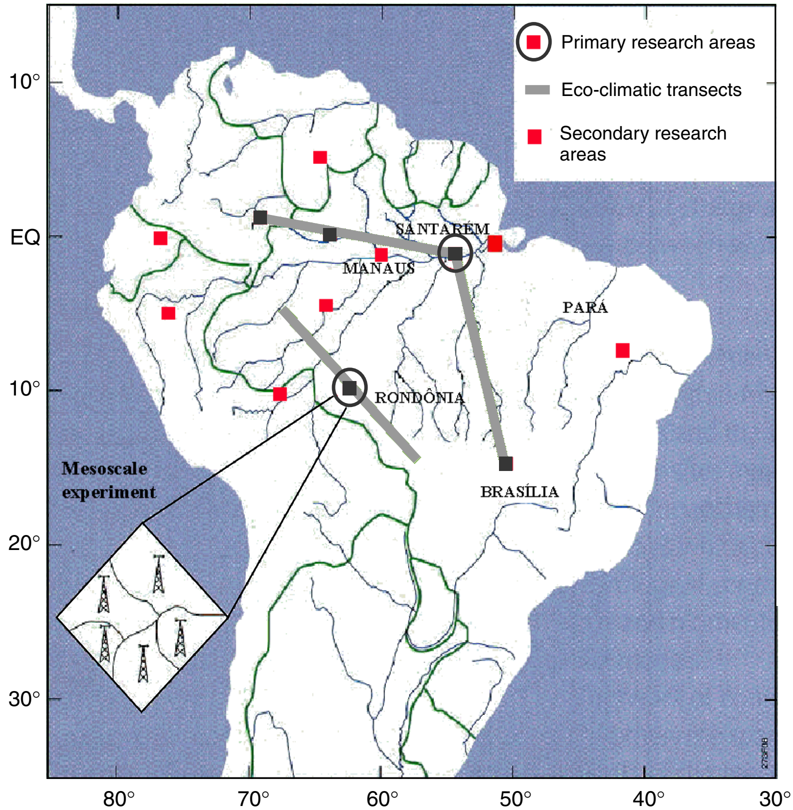


FIGURE 2.7 Map showing the research areas in the Large-Scale Biosphere-Atmosphere Experiment in Amazonia. Primary research areas are part of the two eco-physiological and land-use transects. Secondary research areas will be established over the entire Amazon basin. SOURCE: Courtesy of the Large-Scale Biosphere-Atmosphere Project Office, Brazil.

Measurements, Experiments, and Models of Ecological Organization at Genotype to Community Levels

We need to develop techniques and undertake research to determine the variability that functional diversity introduces into the adaptability of ecosystems. This subject is one of many that must be integrated into our understanding of biodiversity, but it must also be addressed explicitly in the context of global change. It should be researched through a partnership between the global change and biological diversity communities. Research on this topic is internationally coordinated by Focus 4 of the IGBP Global Change in Terrestrial Ecosystems

Core Project, by the UNESCO Man and the Biosphere DIVERSITAS program (Programme Element 2) for terrestrial systems, and by the IGBP Global Ocean Ecosystem Dynamics (GLOBEC) program for marine ecosystems. Aspects of ecosystem function that must be addressed include, but are not limited to, carbon exchange, nitrogen cycling, productivity, albedo, and hydrological processes.

Most analyses of global terrestrial ecosystems have lumped plant species into a small number of "functional" types (usually less than 30) relative to the immense diversity revealed by local studies. However, as models and experiments become more sophisticated, it has become apparent that plant species and functional type characteristics may greatly affect processes at large scales.[95] The role of microbial, fungal, and faunal diversity in large-scale ecology is just beginning to receive attention.

In marine ecology the interaction of trophic levels with physical processes is central. Whereas all animals in the sea are affected to some degree by the dynamics of the waters around them, it seems likely that planktonic animals are the most tightly controlled by the physics of the fluid medium. Since the majority of marine animals spend at least part of their lives in the plankton, research will have to focus on zooplanktonic organisms, both holoplankton and meroplankton. The holoplankton, such as numerous copepods and other macro- and microzooplankters, complete their entire life cycle in the plankton. Most nektonic animals—the large swimming forms such as fish and squid—also have at least one planktonic life stage during which they too are at the mercy of the fluid motions of the sea. Accordingly, success of recruitment into the adult population for marine animals does not depend on biological processes alone. The transport of organisms into regions that may be either favorable or inhospitable plays a major role in dictating the success of recruitment and thus the abundance of marine animals. Moreover, the characteristics of a region that determine its suitability for any given organism include not only the availability of food and abundance of predators but also the dynamic physical features of the local environment that influence the success of recruitment, efficiency of feeding, and susceptibility to predation.

Several issues arise in investigating the relationship between organism-level functional diversity and ecosystem function. First, what is the relationship between biological diversity (number of species) and functional diversity (number of species groups that differ with respect to a given aspect of function—for example, trophic characteristics, drought resistance, or nutrient use efficiency)?

- Do systems contain more functionally different species when they contain more species overall?
- If so, how do the two characteristics scale?

Second, what impact does functional diversity have on long-term ecosystem dynamics? Analysis has shown that increased diversity increases stability but also that diversity may contribute to vulnerability to perturbation.[96]

- What effects does the functional diversity of species have on ecosystem function within biomes and at the global level?
- How different is global NPP, carbon storage, and trace gas production in a world with highly diverse biota, as compared to simplified biota?
- Could potential changes to global biodiversity affect global NPP, trace gas exchange, or other critical aspects of ecosystem function?

The above questions should be used to guide a careful program of hypothesis development and testing. Both models themselves and the use of model systems for experimental studies in natural and managed landscapes are crucial. Aspects of functional diversity must be included explicitly in dynamic global vegetation models and biogeochemical models. Potential future biodiversity losses could affect global ecosystem function. The issue of functional diversity links the interdisciplinary science of global change to some of the core questions of ecology and should motivate a strong research program.[97]

Summary: Key genotype to community measurements

- Measurements of ecosystem function in experiments in which diversity is manipulated.
- Measurements of ecosystem function in "control" and inadvertently modified systems where diversity has been altered by extinction or invasion.
- Coordinated measurements of diversity and function in regional-scale studies.

LESSONS LEARNED

Need for Long-Term Studies and Time Series Measurements

The analysis of long observational time series has been an important feature of global change research. While many of the USGCRP planning documents for ecology emphasize long-term experimental manipulations, several do not even mention long-term observations. This may be historically consistent with ecology's past as a largely experimental field and the structure developed for global change research, but much has been gained from minimally intrusive long-term observations. Ecologists, who have always used such data opportunistically, have derived from statisticians and earth scientists rigorous analytical methods of observational records (using time series analysis and inverse modeling). Large-scale ecology includes problems that, for logistical or ethical reasons, cannot be addressed by direct manipulation (like some problems in geology and medicine). Despite favoring experimental manipulation as a means of hypothesis testing, ecology must increasingly rely on rigorous methods using observational data to test hypotheses or in conjunction with process studies (experiments).

Long time series are critical for detecting and measuring rates of system change. Many phenomena in marine and terrestrial ecosystems occur over long periods of time, including soil carbon accumulation and turnover, nutrient accumulation, forest succession and plant community responses to climate, ocean circulation changes and consequent physical and nutrient influences on marine ecosystems, and population and evolutionary responses to environmental change.[98]

Long time series are also critical for model validation. Global change encompasses changes to many environmental controls over ecosystem processes. Potential consequences of global change include changes to climatic means and extremes, large-scale changes in ocean circulation, changes in ultraviolet radiation, atmospheric deposition of toxins and nutrients, trophic changes, species invasions or extinctions, and changes in landscape pattern and fragmentation. Experimental studies cannot consider all of these influences in factorial combination for logistical and technical reasons, nor can we feasibly imagine all of the potential combinations of variables that could occur. As ecosystems are monitored over time, they experience an increasingly wide range of combinations of environmental variables. By observing ecosystem responses to increasingly many combinations of variables, models (whether quantitative or conceptual) can be tested under a wide range of conditions.

Observational and experimental studies, sustained for years to decades, have played a crucial role in conclusions about ecosystems at large scales. The global observations of CO_2, beginning with Keeling et al.'s Mauna Loa record, have provided an increasingly rich resource for ecosystem studies[99] (see Figure 2.8). The observed increases in atmospheric CO_2 provide a key constraint, together with estimates of anthropogenic emissions (from fossil fuels, cement production, and land-use change) on estimated changes to terrestrial metabolism (hence the so-called missing sink).[100] The seasonal CO_2 cycle, evident as an annual time-scale oscillation in atmospheric concentrations, has also provided a crucial tool for understanding ecosystem behavior.[101] More recently, the spatial distributions of CO_2 and $^{13}CO_2$ have provided critical information identifying the existence and location of a region of terrestrial uptake. In the 1990s measurements of atmospheric oxygen (O_2) were initiated and have likewise proved to be complementary to CO_2 and $^{13}CO_2$ measurements and of great value in confirming the role of terrestrial processes relative to oceanic processes[102] (see Figure 2.9).

Terrestrial time series observations on plot scales (less than 10 m^2) to ecosystem scales (tens to several thousands square meters) have likewise been crucial. Time series observations of plant production (NPP) from grasslands around the world formed the centerpiece of an international collaboration organized by SCOPE.[103] These datasets were used to understand the common principles relating grassland processes to climate and to validate a model of those processes and in a global-scale assessment of the potential responses of grasslands to climate

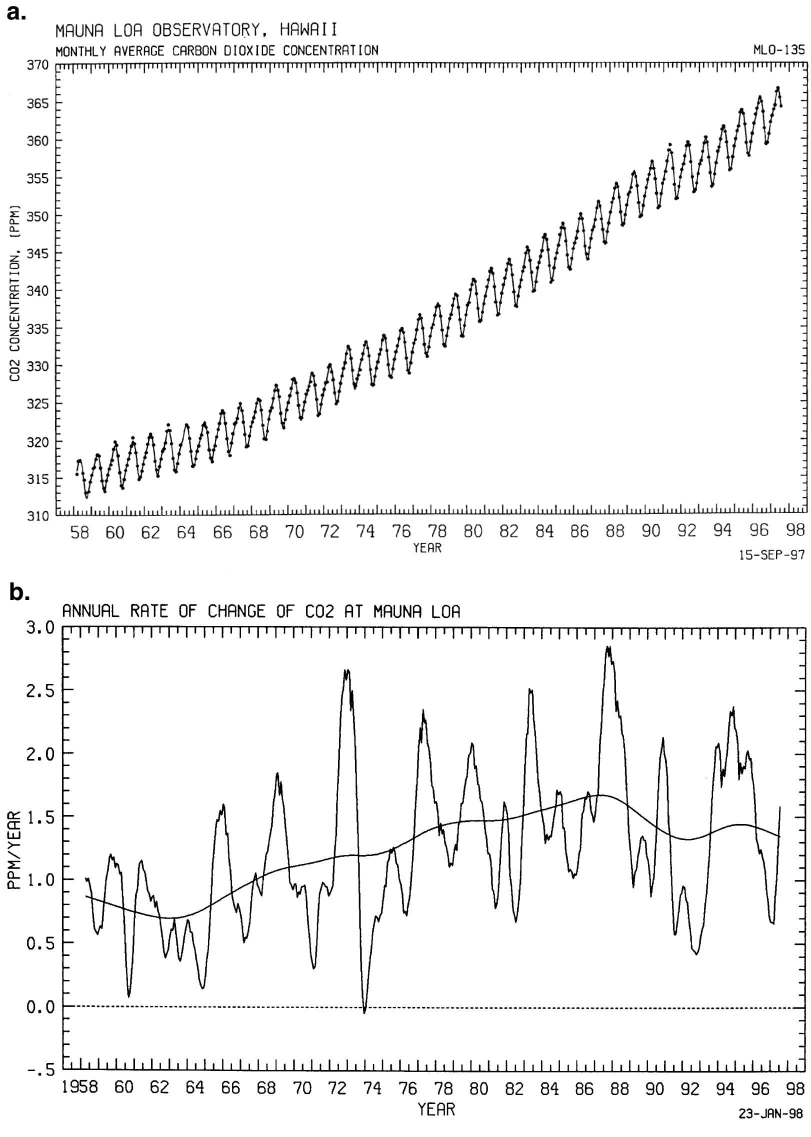


FIGURE 2.8 (a) Monthly average atmospheric carbon dioxide concentration at Mauna Loa Observatory, Hawaii. The smooth oscillating curve is a fit of the data to a trend plus the annual cycle, which increases linearly with time and does not try to connect all of the monthly data points, shown as dots. SOURCE: Adapted from Keeling et al. (1989). Courtesy of the American Geophysical Union. (b) Annual rate of change of carbon dioxide concentration at Mauna Loa. SOURCE: IPCC (1996), as updated by Keeling et al. Courtesy of the Intergovernmental Panel on Climate Change (IPCC).

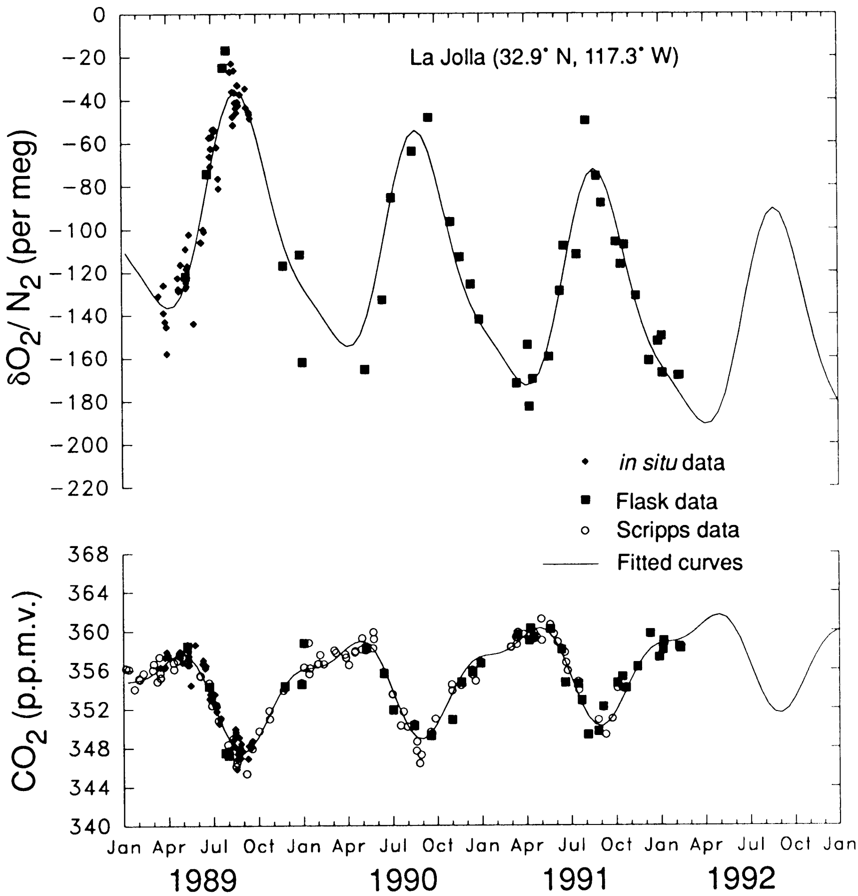


FIGURE 2.9 Measurements of $L(O_2/N_2)$ and CO_2 mole fraction at La Jolla, California. The axes are scaled (5 per meg = 1ppm) so that changes in $L(O_2/N_2)$ and CO_2 are directly comparable on a mol O_2 to mol CO_2 basis. ■, Averages of flasks taken on a given day. ◆, Daily averages for background conditions using the continuous in situ measurement method. **o**, Supplementary CO_2 data from programs at the NOAA Climate Monitoring and Diagnostics Laboratory and the Scripps Institution of Oceanography. SOURCE: Keeling and Shertz (1992). Courtesy of Macmillan Magazines Ltd.

change. Experimental plots established and sustained for over a decade by the NSF's LTER program in temperate grasslands have led to critical understanding of the role of species diversity in sustaining ecosystem processes through drought cycles and of the impact of cumulative nitrogen stress on ecosystem carbon storage and nitrogen cycling. In all this work, observations spanning substantial interannual variability (e.g., Kursk, Russia, 29 years) were critical because the responses of ecosystems to changes in temperature and precipitation were actually observed.

Long-term observations of net CO_2 exchange (NEE) using micrometeorological techniques are also providing a new window on ecosystem sensitivity to climate. Eddy covariance measurements of CO_2 exchange display the observed correlation at high frequency (~10 Hz) between vertical air motion and CO_2 concentration to compute a flux. Prior to the 1990s, this method had only been used in a "campaign" mode to study the short-term processes governing exchange as a function of light intensity, temperature, and turbulence characteristics. Beginning in the early 1990s, a long-term effort was mounted at the Harvard Forest in Massachusetts. That time series now spans unusual freeze conditions, a major drought, and other weather fluctuations and provides information on the response of NEE to climate[104] (see Figure 2.10). Continuing and expanding the network of global observations of concentrations and fluxes (CO_2, $^{13}CO_2$, $C^{18}O_2$, O_2, CH_4, etc.) is mandatory. Measuring fluxes in a range of ecosystems must be one goal of a network.[105] Another goal is to test the quantitative relationships between climate and other drivers and ecosystem responses, a goal that appears to require measurements replicated within vegetation types and along environmental gradients.

Several key lessons can be distilled from the scientific community's experience with time series measurements.

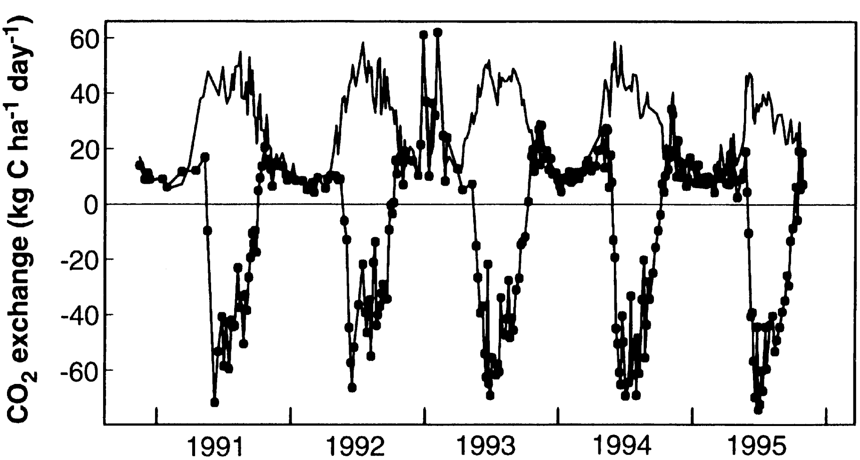


FIGURE 2.10 Daily net CO_2 exchange (NEE) (filled symbols connected by lines) and daily respiration (R) (solid line) during five years at Harvard Forest. Observations are means for four days. SOURCE: Goulden et al. (1996). Courtesy of the American Association for the Advancement of Science.

- First, the measurement should be designed around a question. Even if serendipity eventually intervenes, so that a program addresses initially unforeseen questions, more focused and successful programs emerge when they are based on initial hypotheses.
- Second, the time series should include both the response of interest (e.g., atmospheric CO_2 or net primary productivity) and the hypothesized controls over the response variable's dynamics. Without observations of both cause and effect, rejecting incorrect explanations of observed temporal dynamics is often impossible.
- Third, data management and quality control, including metadata, must be excellent. Changes in methodology, calibration, location, and external influences (adjacency effects) must be documented over time. If not, the data will be compromised for time series analyses or needless effort will be spent on data archeology. Support for the assembly, maintenance, and distribution of datasets for synthetic ecological research must increase.
- Fourth, ecosystem scientists have learned much from both long-term experiments and long-term observations. Long-term observational studies, designed to address specific questions, are fundamental to understanding the interaction of ecosystem and climate system processes. Rigorous methods for the analysis of observational data must be used, adapted, and implemented. The requirements of rigorous data analytical techniques must be considered when designing long-term studies. Overall, a balance between manipulative and observational studies must be preserved.

Multiscale Investigations

Ecological processes inherently occur at multiple scales in space and time. The existence of controls at multiple scales is effectively illustrated by transpiration, the loss of water from leaf surfaces. At the leaf level, transpiration occurs through tiny pores on leaf surfaces called stomata and is controlled by the stomatal aperture, itself under physiological control. At the level of an entire plant, transpiration is controlled by the aggregate of leaf-level water losses.[106] At this level the amount of leaf area and light, temperature, and physiological gradients within the plant's canopy add regulation by canopy architecture, allocation of carbon and nitrogen, and leaf optical properties (which influence light extinction).[107] At yet larger scales, transpiration is influenced by boundary layer humidity and is thus controlled by the aggregate of water loss over many plants, by advection and mixing in the atmosphere, and by the effect of latent heat (water vapor) exchange on atmospheric mixing and turbulence.[108]

On longer timescales, transpiration is influenced by climatic regulation of vegetation, by physiological adjustment to prevailing environmental conditions, and by long-term influences of climate on vegetation types. There is abundant evidence for an adjustment of leaf area to an equilibrium with prevailing soil moisture conditions. This occurs both within vegetation types and through the distribution of species and ecotypes along moisture gradients.

Terrestrial nitrogen cycling exhibits similar scaling. On short timescales, nitrogen availability is determined by the biophysical regulation of the activity of soil microbes, with nitrogen mineralization increasing as conditions become more microclimatically favorable for soil biological activity. On somewhat longer timescales, nitrogen cycling is greatly influenced by changes in litter organic chemistry, which may change with the growth stages of a plant or over successional changes, as species with different litter chemistries change in abundance over time.[109] At longer timescales yet (centuries), nitrogen cycling may be dominated by changes in the amount of nitrogen contained in the ecosystem, controlled by the balance between inputs from the atmosphere and outputs to the atmosphere and hydrological cycle. Thus, variations in atmospheric deposition at mesoscales or larger, and in hydrology at the watershed or larger scale, are key controls on N cycling over very long timescales.[110]

Nitrogen cycling in marine ecosystems is similarly dominated by a fast cycle on short timescales, governed by local trophic interactions and microbial recycling. But on seasonal to millennia timescales, transport of nitrogen to the euphotic (sunlit) zone is controlled by the coupling of large-scale ocean circulation to ocean biogeochemistry.[111] Variations in nitrogen supply occur spatially on length scales of hundreds to thousands of kilometers and on timescales associated with interannual variability in coastal upwelling (e.g., N availability varies with the ENSO cycle) to longer timescales associated with variations in global ocean circulation (decadal to glacial-interglacial timescales).[112]

Because of these multiple scales of regulation, issues of scale are critical in ecology. This fact has long been recognized: the first science workshop explicitly charged with addressing the science agenda of the IGBP produced the volume *Scales and Global Change*.[113] Over the past decade a number of projects have addressed ecological problems and ecosystem-atmosphere exchange at multiple scales. This approach has been extraordinarily fruitful and has also catalyzed successful interdisciplinary interactions (e.g., regarding the intersection of physiological and boundary layer meteorological controls over transpiration).

It has proved resolutely difficult to extrapolate from basic enzymatic or physiological controls to large scales and long time intervals because of the hierarchy of control across scales. For example, in the early 1980s the problems of calculating whole-plant or ecosystem photosynthesis from first principles of leaf physiology seemed intractable and empirical models dominated.[114] Two developments changed this situation. Work on leaf physiology along light extinction gradients within plant canopies demonstrated regularities in the relationship of canopy environmental variables to leaf physiology. The development of eddy covariance measurement techniques also allowed canopy flux measurements to be made so that the "answer" to the problem of scaling leaf gas exchange to the canopy was known. Today there are many successful models of ecosystem CO_2 exchange based on first principles of photosynthesis and stomatal regulation. Two lessons can be learned from this research example and from experience with multiscaled measurements in general:

- First, measurements of phenomena and their controls on multiple scales are crucial to knowledge at large scales. Fine-scale knowledge allowed studies of the environmental patterns of controlling variables to be appropriately designed. Large-scale measurements then provided a scaling theory for extrapolation.
- Second, extrapolation to ecosystems and the globe from just the fine-scaled or "fundamental" body of knowledge can lead to confusion, stasis (as large-scale model predictions and observations persistently fail to agree), or fundamental error. For example, in the absence of a scaling theory for leaf physiological characteristics within the canopy, model error propagation dominated simulations of canopy photosynthesis.

Need for Technical Infrastructure in Ecology

Major advances in understanding terrestrial ecosystems have resulted from the use of new measurement and data analytical techniques. Such measurement techniques have included flux measurements by eddy covariance, isotopic measurements, remote sensing of vegetation canopies, and measurements of atmospheric O_2. New inference techniques, especially the application of inverse modeling techniques, also have been important. The infrastructure for the development of new technologies and their adoption and implementation is weak in ecology. There are few institutions providing engineering, instrumentation, or electronics support for ecologists, and relatively few ecologists receive training in advanced instrumental techniques. Only in the past few years have disciplinary ecologists received rigorous training in remote sensing, and the number being trained with the technical know-how to effectively participate in the design of new sensors is still small. Ecology has no equivalent of the major facilities and engineering staffs supported for the atmospheric sciences by the National Center for Atmospheric Research or for oceanography by the major oceanographic research centers and the University National Oceanographic Laboratory System. In ecology, long-term funding commitments analogous to those for research vessels, advanced instruments, and aircraft tend to be made to field stations, which for the most part do not support the development of new observing technology.

Thus, the suite of advanced techniques that have transformed our understanding of ecosystems (flux measurements, isotopic techniques, remote sensing, inverse modeling, atmospheric oxygen) have largely originated outside ecology. Ecologists, however, have effectively adopted techniques from other fields: for example, flux measurements from atmospheric chemistry and micrometeorology and isotopic techniques from geochemistry. The interdisciplinary projects sponsored by the USGCRP (e.g., Arctic Systems Science [ARCSS], FIFE, BOREAS, Oregon Transect Ecological Research) have resulted in many more ecologists becoming exposed to flux measurements, advanced instruments, aircraft platforms, and remote sensing techniques. The ability of ecologists to adapt and, where necessary, to develop new measurement techniques must be enhanced. As the opportunities for space missions initiated by principal investigators increase, there should be a growing cadre of ecologists with the technical expertise to design and implement remote sensing missions, from instrument and spacecraft design through algorithms and data analysis. At a minimum, training and apprenticeship opportunities for students and practitioners of ecology in instrument principles and development can be expanded. Beyond that, partnerships with national labs, with disciplines containing more expertise in instrumentation and instrument development, and with the private sector could all be encouraged. Precedent exists for both of these approaches, and concern over ecology's technological weakness is not new.[115]

Increased adoption of advanced inference techniques should also be fostered. The situation in this case differs somewhat from that for instrumentation. Many ecologists are familiar with advanced statistical and simulation modeling techniques. Many ecologists possess strong mathematical and computational skills,[116] and biologists have appreciably contributed to the development of mathematics. Encouraging the application of advanced techniques for interpreting observational data and for model-data fusion will build on a strong foundation. There are clear needs for the infusion of quantitative inferential methods such as time series analysis, Kalman filters, data assimilation and adjoint techniques, inverse modeling, and many other approaches in ecology, as well as novel adaptation of these methods to important ecological problems. A series of workshops, tutorial publications, and apprenticeship opportunities could accelerate the adoption of new inference techniques in ecology. Partnerships among agencies supporting ecology and applied mathematics and statistics could provide a valuable funding vehicle for this process.

Several lessons may be drawn from the experience of the past decade.

- The capability to adopt and develop advanced technology requires an investment in supporting infrastructure; such an investment is made in many disciplines.
- Training of ecological scientists, postdoctoral fellows, and students in advanced technologies to produce a cadre that can develop new technologies and be more effective partners with technologists would be of great value to the field.
- Advanced inference techniques have been a critical force in advancing the physical global change disciplines. Many of these techniques (e.g.,

data assimilation, inverse modeling) are foreign to the training of most ecologists, who often have strong quantitative backgrounds. Joint projects and workshops with applied mathematicians and statisticians could quickly transfer such advanced techniques to ecologists.

Organizing Interdisciplinary Ecosystem Science

As global change research has evolved over the past decade or so, considerable work has been done at the interface of ecology, traditionally thought of as a life science, and the earth sciences, especially atmospheric science and geochemistry. Some of the major advances have come in studying the carbon cycle. The carbon cycle exemplifies a science area where rigorous interdisciplinary research is needed, and lessons from this research area are informative about how interdisciplinary science can function with excellence, as well as its potential weaknesses. Similar lessons could be drawn from studies of vegetation and hydrometeorology and of biological sources of trace gases. Study of the carbon cycle required an interdisciplinary approach for several reasons:

- Both terrestrial and marine biological processes are central to its regulation.
- Inference from measurements of carbon in the atmosphere and oceans requires a profound knowledge of transport processes in fluid media.
- The carbon system is perturbed by human land use and energy production, requiring the linkage of natural science inquiry to the social and economic sciences.

An analysis of carbon cycle research allows the strengths and weaknesses of the USGCRP's support for interdisciplinary research to be assessed. Many seminal papers on the carbon cycle emerged as the authors found they had common problems and joined forces, rather than being written by groups of people specifically funded to work together.[d] Many of the collaborations were in fact international. For example, by the mid-1990s, papers utilizing CO_2 concentrations and isotopes were typically authored by interdisciplinary teams collaborating informally. This work was motivated by excitement about what could be accomplished by pooling knowledge, by the self-evident importance of the problem scientifically and societally, and by a sense of healthy competition with other informal teams. The arena for much of this work was found in meetings for which ecologists and a broad range of earth scientists were funded to examine interdisciplinary linkages, such as the carbon cycle symposia of the late 1970s

[d] Papers cited in the 1990, 1992, 1995, and 1996 IPCC assessments of the carbon cycle served as a database.

and early 1980s and more recently such forums as the Office of Interdisciplinary Earth Sciences (OIES) Global Change Institutes and the German Dahlem Conferences as well as at IGBP, European Space Agency, and American Geographical Union meetings.

This working style was also sustained by a funding environment that, although relatively healthy, provided few opportunities for atmospheric scientists, oceanographers, and ecologists to seek funding together through a single venue. Regardless of the success of symposiums such as those just mentioned, joint research programs have been much more difficult to initiate. An NRC *News Report* article described the Tropical Oceans and Global Atmosphere (TOGA) program in its early days as follows: "Research efforts were strongly divided between meteorologists and oceanographers, and the disciplinary boundaries were significant" but as a result of TOGA, "meteorologists and oceanographers worked together, crossing disciplinary and institutional barriers in universities and government."[117] This could well be a description of the current state of carbon cycle research and how it might change—especially with respect to institutional barriers in government. While barriers exist between atmospheric, ecological, and ocean scientists, the interagency Terrestrial Ecosystems initiative may be a model for future carbon science programs as it allows several agencies to jointly manage a combined competition for ecologically oriented proposals. A joint review of all proposals is conducted on the basis of scientific merit without great attention to which agency will ultimately fund the proposal. Although great progress has been made in understanding the carbon cycle—accompanied by a liveliness reflecting the informal and collegial nature of the program—the fragmentation of the problem has produced one demonstrable weakness. Because there is no "U.S. National Carbon Cycle Research" agenda, it is very difficult to evaluate the state of knowledge of the field as a whole and or to establish research priorities. Whereas this can be done within disciplinary areas (e.g., atmospheric science, oceanography) or occasionally within agencies, integration cannot be achieved for the field. Perhaps as a consequence, while great progress has been made in some areas, some questions have persisted for decades. Even within the IGBP the carbon cycle is just emerging as a coherent program-level activity, spanning the terrestrial Global Change and Terrestrial Ecosystems Core Project, oceanic (JGOFS, Land-Ocean Interactions in the Coastal Zone, IGAC), and integrative (Global Analysis, Interpretation, and Modeling) programs.

Several key lessons for interdisciplinary research can be extracted from this history.

- First, the excitement and rewards of working in important areas are sufficient to motivate a significant amount of research, major commitments to collegial collaborations, and progress. This occurs even in the absence of a formal program to address a problem. The effort on the carbon cycle, which is not funded in a coordinated manner or attacked as a USGCRP priority, is an apt comparison to the programmatic approach taken to El Ninõ-Southern Oscillation or stratospheric O_3.

- Second, the absence of either a formal program for carbon cycle research (along the lines of TOGA) or the rigidity of the standing programs (e.g., the disciplinary programs at NSF) restricts the full participation of the scientific community. Programs intended to promote interdisciplinary team building can be effective in developing "institutes without walls," as alternatives to center- or institute-style programs. Supporting this conjecture, university investigators in collaborative programs such as NSF's JGOFS, LTER, and ARCSS programs and the National Aeronautics and Space Administration's Mission to Planet Earth (MTPE) program seem disproportionately important contributors to the interdisciplinary literature.
- The development of effective interdisciplinary teams, especially those that cross major disciplinary boundaries (e.g., life and earth sciences), requires the existence of stable support aimed specifically at interdisciplinary questions. Such awards need not be large per principal investigator, but they must meet at least three criteria: (1) they need to be in place long enough to allow the development of effective interdisciplinary communication; (2) the group must be explicitly reviewed on its ability to function as a team; and (3) the project must be judged high-quality science on the basis of initial and, for long-term projects, ongoing and rigorous peer review. The last criterion is crucial both for recruitment of top scientists into such partnerships and for community acceptance of nontraditional funding vehicles. Long-term, problem-oriented, team-oriented, peer-reviewed research should be a part of the large-scale ecosystem research funding portfolio. Such investigations should be available for a wide range of science problems as the scientific agenda continues to evolve. When research areas, like the carbon cycle, require the partnership of disciplines whose funding mechanisms are not traditionally coordinated, mechanisms must be developed to allow the establishment of problem-oriented rather than disciplinary priorities within and across agencies.

RESEARCH IMPERATIVES

Again, critical Research Imperatives for ecosystem studies in the USGCRP for the next decade include the following:

- *Land surface and climate:* Understand the relationships between land surface processes and weather prediction and changing land cover and climate change.

- *Biogeochemistry.* Understand the changing global biogeochemical cycles of carbon and nitrogen.
- *Multiple stresses.* Understand the responses of ecosystems to multiple stresses.
- *Biodiversity.* Understand the relationship between changing biological diversity and ecosystem function.

Observations and Experiments

Research on global ecosystem processes motivates four broad classes of observations and experimental studies. As noted in the section "A Research Agenda for the Next Decade," large-scale measurements in ecology tend to support all of the Research Imperatives above in a crosscutting fashion, with any one measurement set helping to test a variety of hypotheses. The four key measurement areas are the following:

- Time series observations of ecosystem state.
- Land-use and land cover change.
- Site-based networks.
- Measurements of diversity, functional diversity, and ecosystem function.

Time Series Observations of Ecosystem State

Global time series of vegetation and phytoplankton state, derived from NOAA's AVHRR and Coastal Zone Color Scanner sensors, for land and ocean, respectively, have proven their value in understanding the seasonal and spatial characteristics, interannual variability, and trends of large-scale biogeochemistry and biophysical processes.[118] Space-based measurements of ecosystem state are fundamental in determining the link of terrestrial ecosystems to climate, the biogeochemistry of the land and oceans, and the impacts of climate and other disturbances. While the measurements of "greenness" and ocean color are not direct ecological properties, they have proven to be highly correlated with the spatiotemporal dynamics of ecosystems. Recent work highlights both the utility of these records and the dependence of the science on long consistent records.[119] Stable calibration and removal of the atmospheric signals of ozone, water vapor, and aerosols are critical to detecting ecological signals. While there is ample room for innovation in land surface remote sensing, stable calibration and correction impose stringent requirements on the sensor or sensors deployed. New instruments, while adding new capabilities, must also be "backwards compatible" to preserve time series. Atmospheric correction requires that coincident observations to quantify water, ozone, and aerosols be available for use in land surface retrieval algorithms. Spatial resolution and temporal resolution for time series instruments are typically a compromise (0.25 to 1 km^2) between sufficiently high spatial resolution to resolve ecosystem structure and swath width and data rate limitations associated with near-daily coverage. High temporal coverage is needed to ensure adequate sampling of seasonality, especially in cloudy environments. These requirements apply generally for both terrestrial and marine ecosystems: marine ecosystems add additional instrument requirements to avoid saturation by sun glint or high reflection. Note that data for land cover change require higher spatial resolution but lower temporal resolution.

Land Cover, Land Use, and Disturbance

Changing land use and land cover are fundamental drivers of global change and are direct reflections of human activity and impacts. Land-use changes have profound effects on the biogeochemistry of carbon, infrared-active gases, photochemically active gases, and aerosol production (via dust and biomass burning). Land-use changes also affect hydrology and erosion and by changing surface albedo and energy exchange can have direct effects on climate. People often create highly heterogeneous landscapes—mosaics that may encompass activities with highly divergent effects on ecological processes. The spatial arrangement of landscapes can affect exchanges of water and associated solutes and particulates in freshwater and coastal margin areas, with land cover at the land-water margins having substantial effects on water chemistry. The arrangement of landscapes also affects biological diversity, pests and pathogens, invasiveness and extinctions. Data on land cover and its change over time must thus capture the spatial scales of natural and human patterns. Space-borne sensors with resolutions from a few square meters to tens of square meters have proven to meet these needs.[120] Sensors with two to seven spectral bands are adequate for land-cover mapping, although new technology using spectrometers,[121] radar, or lidar has great potential to provide new information. As in measuring ecosystem state, backwards compatibility must be preserved to continue existing time series when new technologies and capabilities are introduced.

Site-Based Networks

In situ measurements of ecological processes tend to be highly multivariate. In terrestrial systems, understanding a measurement of CO_2 flux and determining NPP require sampling multiple plant parts (leaves, wood, roots), often of several life forms (e.g., co-occurring grasses, shrubs, and trees). The plant parts are then analyzed for carbon and nitrogen. Understanding spatial variations in gradients of atmospheric CO_2, $^{13}CO_2$, CO, ^{18}O, or O_2 requires a network of such sites over large areas. To understand process, leaf physiology, soil microbial processes, water fluxes, and other variables must be determined. Parallel issues arise in marine ecosystems regarding trophic dynamics and transport. At many sites these measurements are made as part of an experimental design including controls and various manipulations (e.g., of nutrients, species composition, disturbance frequency). These measurements are the essence of ecological data: the satellite and other geographic data serve to knit together disparate process studies in space and time. While there is much interest in a common set of quantities in ecological site studies (quantities such as CO_2, trace gas and water fluxes, NPP, nutrient availability, and species composition and diversity), achieving consensus on a core set of measurements, standard methods, and data formats is just beginning. No global-scale experimental design implementing such sites is in place to sample the marine and terrestrial ecosystems (such a design is proposed by the IGBP, using long baseline transects across ecological gradients). A high priority of global ecosystem science is to develop a network of appropriately sited atmospheric concentration and isotope, flux, and ecological process sites. Both the overall experimental design and the suite of measurements and methods must be decided. Minimally intrusive measurements (e.g., flux measurements) and manipulations (e.g., of CO_2 concentration) must be components of such a network design.

Measurements of Diversity, Functional Diversity, and Ecosystem Function

The issue of diversity and species composition changes has emerged as a critical topic of global change in recent years. It is clear that the functional diversity of the Earth's biota is a first-order control over global ecosystem function, but how changes to the biota will affect global ecosystem function still is a young research topic.[122] Designing a global observing system and network of experimental studies, analogous to those described above for biogeochemical fluxes, is premature; the necessary monitoring and manipulations at global scales are currently far from obvious. But a major exploratory effort involving manipulations, studies of ecosystem function in the face of ongoing invasions, extinctions, and species range shifts, along with global monitoring of species diversity, invasion, and extinction rates, are all needed. These exploratory studies will lay the groundwork for a more systematic attack. The foundation for systematic study and monitoring of changing diversity and functional diversity must be laid quickly and a global research program put in place.

Modeling and Theory for Integration in Time and Space and Across Ecological Levels of Organization

Models of ecosystem processes have become fundamental tools in Earth system science. The development of models over the past five years has been extremely rapid, and ecosystem models have become important parts of coupled climate system models, analyses of contemporary global data, and assessments of global change.[123] Currently, global terrestrial ecosystem models fall into three broad categories: (1) biophysical models that address the exchange of water, energy, and carbon on minute to seasonal timescales, such as the "fast water-carbon-energy system"; (2) biogeochemical models that address the dynamics of carbon, nitrogen, water, and energy on monthly to centennial timescales and that focus on carbon storage; and (3) biogeographic models that simulate the response of vegetation ("biome") distribution to climate and other factors[124] (see Plate 4, Table 2.2). The next generation of models, the so-called dynamic global vegetation models, couple the above three types of models because the time-dependent change of vegetation results from interactive biophysical, biogeochemical, and population-community processes.[125]

Marine ecosystem models often simulate the coupled dynamics of carbon and nutrients (usually nitrogen) but differ from terrestrial ecosystem models in that the focus, even in biogeochemical models, is much more on trophic interactions. The understanding of processes that determine abundance, fluctuation in abundance, and production of marine animals must necessarily involve coupled physical-biological models, linking performance of the individual organism to local physical processes, and linking both the biology and local physics to basin-scale changes in global climate. Modeling is expected to play an increasingly significant role at several levels. The explicit incorporation of physical variables and processes in biological population models holds promise for great originality and progress. Appropriately constructed models of both physical and biological processes should guide the choice of field experiments and observations, while results of those field exercises should feed back interactively into the models.

Clearly, ecosystem models are an important aspect of data analysis, experimental design, and prediction in ecology. For terrestrial and marine ecosystem models to become powerful and credible tools for disciplinary and interdisciplinary science and more useful for assessment, rapid progress must continue. There are a number of imperatives for the development of improved models.

- Global models and key datasets should be continually related, with models being compared to observations and experiments and new observations and experiments arising from model uncertainties and failures. Ecosystem modelers and observationalists must work together to define data requirements for operating and evaluating ecosystem models.[126]
- Models are becoming essential to understanding complex datasets in ecology.[127] Advanced data-model fusion techniques, such as data assimilation, adjoint modeling, and inverse modeling, must join the ecological tool kit.
- Currently, few ecosystem models include both intensively managed and wildland ecosystems. Many global and regional experiments are done using "potential natural" vegetation. Global models must incorporate the impacts of human land use along with other environmental factors. In addition, although the role of disturbance is central in site- and landscape-level ecosystem models, many global models have simplified the

modeling of disturbance effects.[128] Future models must adequately include the effects of disturbance on ecosystem heterogeneity and on water, carbon, and nutrient fluxes.[129]

- Most global ecosystem models are run using climate as an external driver. Ecosystem models are required that can be run as components of Earth system models for a range of timescales to simulate the coupled effects of changing ecosystems and changing physical and chemical climate. These models must simulate biophysical processes, biotic uptake and storage of carbon, and ecosystem effects on atmospheric CO_2 and other trace gases.
- Changes to the distribution of species and/or functional types will have profound effects on ecosystem functioning. Current models represent the population processes underlying vegetation change in the form of calibrated empirical models. A stronger theoretical basis and scaling theory for large-scale biotic change must be developed.

Long-Term Questions for Ecology and Ecologists

Taking a longer perspective, two issues must eventually be confronted. First, although we have at least the beginnings of a theory for biophysical and biogeochemical processes at larger scales, we lack an integrative understanding of the biological processes that regulate the interactions of ecosystems with global change. Simply put, there is not yet enough biology in our paradigm for global ecology. Currently, global ecosystem models use reasonably general formulations for processes such as photosynthesis and decomposition, formulations that are based in theory and supported by strong empirical evidence. Processes that vary at the organism level, such as energy or nutrient allocation within plants, biochemical plasticity of microorganisms, and trophic interactions, are typically neglected or represented so as to agree with limited empirical data. Responses of processes such as allocation, herbivory, or microbial decomposition to environmental change reflect the genetically constrained adaptability of organisms, genetic variations in relevant traits, and rates of population processes.

On large scales and in the long term these evolutionary constraints may substantially influence the trajectory of ecosystems, but to date we do not have theories or empirical data of sufficient breadth or robustness to predict any biological limitations to adaptation under global change.[130] Because of these unknown limitations, considerable uncertainty exists in quantitative projections of future ecosystem states. Current dynamic global vegetation models use empirical formulations for large-scale controls on plant community processes, rather than making explicit reference to the actual underlying population biology. Developing a more integrated and general theory for the population and biogeographic bases for ecosystem change is a high priority for the long term. Current efforts should be evaluated against this ambitious long-term goal.

Second, with the expectation that human populations and economies will continue to grow, the direct human impact on ecosystems is almost certain to increase. Increased management of the biosphere will be a crucial part of any response to global change to ensure the sustainability of key natural resources in the face of climate change and direct human impacts.[131] In addition, management of ecosystems is an important aspect of mitigation for CO_2 and other trace gases, the emissions of which to the atmosphere are dependent on land cover, fertilization, and other human impacts.[132] Quantitative knowledge of the roles of ocean and terrestrial ecosystems is indispensable for any future agreements to stabilize CO_2, N_2O, and methane. It is essential to assess proposed mitigation measures for greenhouse gas emissions and experimental manipulations with ecosystem models prior to implementing such measures. These efforts may depend on the response of long-lived species such that experimental evaluation would require decades. The economic and nonmarket impacts of ecosystem change are just beginning to be recognized, and these impacts will likely become increasingly important drivers of policy.[133]

As the needs and potential for ecosystem management in environmental mitigation increase, the scientific potential of mitigation must be continually assessed. Attempts at ecological mitigation and restoration have a mixed record of success, and scientific progress does not guarantee that the knowledge required for successful management has been developed. As the global change program advances, the feasibility and value of mitigation through ecosystem management must be assessed continually. Although many proposals for mitigation such as afforestation, as proposed by the IPCC,[134] have great appeal, many of the realized projects are either more difficult to accomplish than originally envisioned[135] or are affected by the "law of unintended consequences"—that is, the mitigation practice has some unexpected environmental consequences. While it is likely that ecologically based mitigation will play an increasing role in environmental management, better understanding at the system level is required for new management strategies to have a high probability of success.

In conclusion, as we look five or ten years into the future of global change research, integration of empirical knowledge and theory of specific systems must be used to produce more general and generally applicable theories, in some cases for phenomena for which we currently have no quantitative understanding. As the human impact on ecosystems becomes ever greater and the motivation to involve ecosystem management in mitigation strategies increases, there is ever-greater need for an improved scientific capability to assess the likely success of proposed manipulations at the system level. Ecology must develop a robust predictive capability for environmental change and management consequences.

NOTES

1. NRC (1986).
2. NRC (1994).
3. Andreae and Schimel (1989); Matson and Ojima (1990).
4. Breymeyer et al. (1996).
5. For example, Keeling et al. (1989) and Tans et al. (1990).
6. For example, Ciais et al. (1995a, b); and Denning et al. (1995).
7. For lab studies, see, e.g., Holland et al. (1995); for field studies on soil warming, see Harte and Shaw (1995); for observational programs, see Oechel et al. (1993); for data synthesis, see Raich and Schlesinger (1992).
8. Terrestrial ecosystems, Jenkinson et al. (1991), Townsend et al. (1992), Dai and Fung (1993), VEMAP Participants (1995), Schimel et al. (1996); marine ecosystems, Kleypas (1997).
9. Ecosystem response to climate, IPCC (1990); temperature and moisture effects on biota, e.g., Raich and Schlesinger (1992); climate and succession, Pastor and Post (1993); climate and nitrogen cycle, Schimel et al. (1994).
10. Oechel et al. (1994).
11. Eddy covariance techniques, Lenschow (1995); NEE, Wofsy et al. (1993).
12. Goulden et al. (1996).
13. Woodwell (1989); Woodwell and Mackenzie (1995).
14. Braswell et al. (1997).
15. Mortality, Smith and Shugart (1993); soils, Jenkinson et al. (1991); nitrogen cycle, Melillo et al. (1993); Schimel et al. (1994); interactions, VEMAP Participants (1995).
16. E.g., Ciais et al. (1995a, b), Schimel et al. (1996), Thompson et al. (1996), Bruno and Joos (1997), Randerson et al. (1997).
17. E.g., Pastor and Post (1986), Schimel et al. (1990), Melillo et al. (1993)
18. Hunt et al. (1996), Schimel et al. (1996), Waelbroeck et al. (1997).
19. Land cover and climate, Anthes (1984), Dickinson and Henderson-Sellers (1988), Pielke and Avissar (1990); land surface processes, Henderson-Sellers (1993), Sellers et al. (1997); international field campaigns, Sellers et al. (1995, 1996c); LBA Concise Experimental Plan, http://www.cptec.inpe.br/lba/conciseplan/cpi06.html.
20. Verma et al. (1993).
21. Canopies, Field and Mooney (1986); canopy modeling, Sellers et al. (1992).
22. Bonan et al. (1992).
23. Farquhar et al. (1993), Flanagan et al. (1997).
24. Paleoclimate, Kutzbach et al. (1996); contemporary weather, Pielke et al. (1992); climate, Shukla et al. (1990); weather forecasting, Pielke et al. (1997); climate projections, Sellers et al. (1996b, 1997).
25. Entekhabi et al. (1992), Sellers and Schimel (1993), Braswell (1996), Hunt et al. (1996), Sellers et al. (1997).
26. FIFE, Sellers et al. (1996c); BOREAS, Sellers et al. (1995); HADEX, André et al. (1989).
27. Potter et al. (1993), Sellers and Schimel (1993).
28. Luizão et al. (1989), Crutzen and Andreae (1990), Mosier et al. (1991, 1997), Keller et al. (1993).
29. Vitousek et al. (1986).
30. E.g., Skole and Tucker (1993); Defries and Townshend (1994).
31. Houghton et al. (1983).
32. Skole and Tucker (1993).
33. Groffman and Likens (1994); Woodward and Steffen (1997).
34. Wedin and Tilman (1996).
35. Lodge (1993), Rejmanek and Randall (1994), Carleton (1996).

36. Vitousek et al. (1996).
37. Niemela and Mattson (1996).
38. D'Antonio and Vitousek (1992).
39. Carpenter and Kitchell (1993), Jones and Lawton (1995).
40. Tilman and Downing (1994), Lawton (1995), Tilman et al. (1996), Wedin and Tilman (1996).
41. E.g., Sellers et al. (1996a).
42. Carpenter et al. (1995).
43. Oechel et al. (1994).
44. Drake (1992).
45. Idso and Idso (1994).
46. Chapin et al. (1995).
47. Harte and Shaw (1995).
48. Wedin and Tilman (1996).
49. Carpenter et al. (1995).
50. Martin (1990).
51. Coale et al. (1996).
52. Chameides et al. (1994).
53. Galloway et al. (1995), Howarth et al. (1996).
54. Peterson and Melillo (1985).
55. Schindler and Bayley (1993), Townsend et al. (1995), Bruno and Joos (1997), Holland et al. (1997).
56. Holland et al. (1997).
57. Ibid.
58. Aber et al. (1989), Schulze et al. (1989), Wedin and Tilman (1996).
59. Schimel et al. (1995, 1996, 1997a, b).
60. Siegenthaler and Sarmiento (1993).
61. Schimel et al. (1995).
62. Krankina and Dixon (1994), Oechel et al. (1994), Archer et al. (1995), Sellers et al. (1995), Brown et al. (1996).
63. Comins and McMurtrie (1993).
64. VEMAP Participants (1995).
65. Friedlingstein et al. (1995), Randerson et al. (1997).
66. Post et al. (1997), Randerson et al. (1997).
67. Schindler and Bayley (1993), Townsend et al. (1996).
68. Pastor and Post (1993), Bolker et al. (1995), VEMAP Participants, (1995), Schimel et al. (1996).
69. Smith and Shugart (1993).
70. VEMAP Participants (1995), Schimel et al. (1997a, b), Kittel et al. (1996).
71. Sponsored by SCOPE, Breymeyer et al. (1996), and the IGBP's GAIM Task Force; Cramer et al. (in preparation) and by Electric Power Research Institute's Carbon Cycle Model Linkage Project.
72. VEMAP Participants (1995).
73. Field, Stanford, personal communication.
74. Schimel et al. (1997a, b).
75. Ibid.
76. Ibid.
77. Schimel et al. (1996).
78. Andreae and Schimel (1989), Ojima and Svensson (1992).
79. Direct effects of climate, Gifford et al. (1997) interactions with nitrogen cycle, VEMAP Participants (1995), Schimel et al. (1996), Randerson et al. (1997); interactions with other stresses, Schindler and Bayley (1993), Townsend et al. (1996), Holland et al. (1997).

80. Chameides et al. (1994).
81. Howarth et al. (1996).
82. Carbon storage, Goulden et al. (1996); trace species, Bakwin et al. (1995).
83. Mosier et al. (1997).
84. Responses to trends, Oechel et al. (1993), climatic events, Schimel et al. (1996), Wedin and Tilman (1996).
85. Cumulative impacts, e.g., Walker et al. (1987); Holland et al. (1997); analyses of land-use effects, e.g., Houghton et al. (1983).
86. *Ambio* vol. 23 (1994), Turner et al. (1995).
87. Asner et al. (1997), Holland et al. (1997).
88. Schimel et al. (1997a).
89. E.g., Dlugokencky et al. (1994), Hein et al. (1997).
90. Bakwin et al. (1995), Hurst et al. (1997).
91. Myneni et al. (1996, 1997); Braswell et al. (1997); Randerson et al. (1997).
92. Sellers et al. (1997), Braswell et al. (1997).
93. Harriss et al. (1994).
94. Groffman and Likens (1994).
95. Bolker et al. (1995), Schimel et al. (1996), Wedin and Tilman (1996).
96. Stability, Lawton (1995); vulnerability, Wedin and Tilman (1996); in their experiment the presence of low C-to-N ratio C_3 plants reduced system-level nitrogen retention.
97. http:\\www.unesco.org/mab/collab/diver1.htm.
98. Pastor and Post (1986), Harden et al. (1992).
99. Keeling et al. (1996).
100. Schimel (1995).
101. Randerson et al. (1997).
102. Keeling and Shertz (1992).
103. Breymeyer et al. (1996).
104. Goulden et al. (1996).
105. *Global Change Biology*, vol. 2 (1996).
106. McNaughton and Jarvis (1991).
107. Schimel et al. (1991).
108. McNaughton and Jarvis (1991).
109. Aber and Melillo (1982).
110. Asner et al. (1997).
111. Najjar (1992).
112. Carpenter and Capone (1983).
113. Rosswall et al. (1988).
114. E.g., Shugart et al. (1988).
115. Hibbard and Shaulis (1997).
116. Levin (1992).
117. NRC (1997).
118. Sellers et al. (1997), Fung et al. (1987), Myneni et al. (1997), Potter et al. (1993), Randerson et al. (1997), Braswell et al. (1997).
119. Braswell et al. (1997) and Myneni et al. (1997).
120. Skole and Tucker (1993).
121. Wessman (1988).
122. Vitousek et al. (1996), Braswell et al. (1997), Schimel et al. (submitted).
123. Models, Sarmiento and Le Quéré (1996), Sellers et al. (1996a); data analyses, Denning et al. (1995), Sarmiento et al. (1995), Schimel et al. (1996); assessments, Melillo et al. (1993), VEMAP Participants (1995), Sarmiento and Le Quéré (1996).
124. (1) Sellers and Schimel (1993), (2) VEMAP Participants (1995); (3) Ibid.

125. Foley et al. (1996).
126. Sellers and Schimel (1993).
127. Ciais et al. (1995a, b), McKane et al. (1997a, b).
128. Ecosystem models, Pastor and Post (1986), Shugart et al. (1988); global models, VEMAP Participants (1995).
129. VEMAP Participants (1995), Schimel et al. (in press).
130. Karieva et al. (1993).
131. IPCC (1995), Wisnewski and Sampson (1993).
132. Schimel et al. (1997b).
133. Watson et al. (1996), Schimel et al. (1997b).
134. IPCC (1990).
135. Joos et al. (1991).

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3

Changes in the Climate System on Seasonal to Interannual Timescales

SUMMARY

Today, we have entered a new age of climate prediction. The past 10 years have witnessed significant advancements in our ability to observe, understand, and predict a year ahead the fundamental dynamics of the El Niño-Southern Oscillation (ENSO) system. We are moving into an era when climate predictions will increasingly affect the prosperity and security of the American people (and people worldwide) through information that will reduce the impacts of destructive natural climate fluctuations, such as droughts, which lead to forest fires and crop failures; floods, which lead to loss of life and obstruction of commerce; and heat and cold waves, which lead to human misery and deprivation.

A dedicated community of government and university meteorologists and oceanographers has achieved swift and remarkable progress. We have already begun to predict aspects of El Niño in the tropical Pacific. These forecasts are used by the affected countries (Peru, Brazil, Australia, Chile, Columbia, the Philippines, and the American Flag Pacific Islands) and have helped to increase the prosperity and security of those countries. The actions taken over the next few years will determine whether this predictive capability can be developed for more productive use in the United States.

Implementation of the Tropical Oceans and Global Atmosphere program and the Global Energy and Water Cycle Experiment demonstrates the feasibility of end-to-end, multidisciplinary scientific analysis within the U.S. Global Change Research Program (USGCRP). In many ways these efforts are pathfinders for work on the some of the central issues of global change. By virtue of ENSO's timescale, the predictions of these efforts can be rigorously tested against observations. *Thus, the capability of making the first genuine dynamic climate predic-*

tions has been demonstrated, and the capability to use these predictions is being developed. In deploying a dedicated observing system in the tropical Pacific, a coherent observational base was created to test and improve predictive models. Data from this observing system have also been made available in real time over the Internet, demonstrating the possibilities of making data freely available in an environment where data and conclusions have commercial and strategic value.

Research Imperatives that must be met to understand climate on seasonal to interannual timescales include the following:

- *ENSO*. Maintain and improve the capability to make ENSO predictions.
- *Global monsoon.* Define and predict global seasonal to interannual variability, especially the global monsoon systems, and understand the extent to which variability is predictable.
- *Land surface exchanges.* Understand the roles of land surface energy and water exchanges and their correct representation in models for seasonal to interannual prediction.
- *Downscaling*. Improve the ability to interpret the effects of large-scale climate variability on a local scale.
- *Terrestrial hydrology*. Understand the seasonal to interannual factors that influence land surface manifestations of the hydrological cycle, such as floods, droughts, and other extreme weather.

INTRODUCTION

Understanding climate variability on seasonal to interannual timescales, especially with regard to the hydrological cycle, offers some of the most direct benefits in all of global change research. In particular, better prediction of precipitation is of special interest because it can change the way people interact with the environment, perhaps in revolutionary ways. Precipitation is a fundamental determinant of climate and human habitability through its relationship to land surface conditions, including soil moisture, snow cover, vegetation, evaporation, stream discharge, and surface temperature. An improved capability to model and predict precipitation variability on seasonal to interannual timescales is therefore of potentially great socioeconomic benefit for water and energy resource management, agriculture, and a variety of other factors related to general human well-being.

In this chapter, case studies highlight recent applications of seasonal to interannual climate prediction, in particular the prediction of precipitation, in geographical areas from Asia to Brazil to the central United States. These cases indicate the promise of climate forecasting and also the issues that such forecasting raises in particular applications.

Some important advances have come from the study of ocean-atmosphere interactions. Some aspects of ENSO are predictable a year or more in advance.[1] This predictive capability for ENSO must not only be maintained and improved but expanded to areas where major benefits can be obtained, notably in exploring the predictability of monsoon systems of North America and Australia-Asia.

Several prominent streams of climate research deal with continental processes—on how land surface properties affect the overlying atmosphere and how climate effects are manifested on land surfaces. Such interactions involving land surfaces offer the potential for applications at local scales, applications that may be the most relevant to people. The slowly changing boundary conditions of the land surface in midlatitudes have also prompted the notion that predictability may lie in the "memory" of such systems. Research has also emphasized the seasonal to interannual factors that influence floods, droughts, and other climate extremes, which drive much of the interest in climate.

The human dimensions of seasonal to interannual climate research are a recurring theme throughout this chapter. The case study in northeast Brazil highlights the significance of climate prediction capability for an agrarian society. Learning to apply seasonal to interannual climate predictions well, for the benefit of human society, is an important research imperative, but it is not directly addressed here. The topic is covered more extensively in Chapter 7.

CASE STUDIES

1982 to 1983 El Niño Inspires Real-Time Measurements

By the early 1980s, much interest had arisen regarding the phenomenon of El Niño, an enhancement of the normally warm oceanic current appearing off the coast of Peru around Christmas time. The El Niño of 1972 to 1973 had coincided with the decline of the Peruvian anchoveta industry, which had supplied 20 percent (by weight) of the world's fish catch. Since anchoveta was a major global source of cattle feed, the precipitous decline of this industry drove up world soybean prices and focused the world's attention on a phenomenon that had previously been assumed to be local to the South American coast.

There was only fragmentary evidence in the 1970s about the causes and mechanisms of El Niño, but there was enough to suggest that El Niño consisted of a large-scale, coupled atmosphere-ocean phenomenon occurring primarily over the wide expanses of the equatorial Pacific, that it had local manifestations near the coasts of Peru and Ecuador, and that it was connected to the interannual variations of east-west pressure gradients called the Southern Oscillation. From that time forward, El Niño was identified as the warm phase of ENSO.

Oceanographic measurements in the equatorial Pacific during the 1960s and 1970s had given oceanographers a set of rules about the sequencing and onset properties of ENSO's warm phases. On the basis of these rules, an El Niño watch was established to "catch" an El Niño when one was about to occur. The rules indicated that one was due in 1975, and many ships were launched to observe the

El Niño, but warm conditions in the tropical Pacific failed to appear (a warm phase of ENSO *did* occur in 1976).

By the early 1980s, papers had appeared that more fully explained the sequence of events during warm and cold ENSO phases and the influence of these warm and cold sea surface temperatures (SSTs) on the rest of the northern hemisphere climate.[2] These important advances, together with establishment of the World Climate Research Program to study the role of the ocean in climate, set the stage for a major international study of ENSO that was eventually to become the Tropical Oceans and Global Atmosphere (TOGA) program. It was Bjerknes's insight that ENSO was an inherently atmosphere-ocean phenomenon that required both meteorologists and oceanographers to cooperate in planning TOGA. The full wisdom of this approach became clear only later when it was realized that the underlying mechanism for ENSO would never have been discovered by meteorologists or oceanographers separately working within their own disciplines.

U.S. scientists met in October 1982 at Princeton University to plan the program. There was much discussion about then-current events in the tropical Pacific. But old ideas and the paucity of data misled everyone. Some even argued vehemently that El Niño could not occur at the same time that the largest warm phase of ENSO in this century (at the time) was already present in the tropical Pacific. In fact, satellite measurements of SST had been rendered ambiguous by the simultaneous eruption of El Chichón, and no other credible in situ network was in place to ground truth the satellite measurements.

Several months later it became clear that the largest ENSO warm phase of the century had taken place largely out of view of the world's scientists, an event leading to the realization that real-time measurements of the tropical Pacific were essential. This experience, in conjunction with the development of a dynamical predictive capability for SST in the tropical Pacific,[3] eventually led to the new TAO (Tropical Atmosphere-Ocean) array of 70 moorings in the tropical Pacific. TAO telemeters back the data on winds and upper-ocean thermal structure to the Global Telecommunication System, from which it is available to all.[a] A 1996 report provides a complete history and extensive references.[4]

Macroscale Climate Variability and Crop Yields in the Monsoon Regions

The annual cycle of the monsoon systems has led the inhabitants of monsoon regions to divide their lives, customs, and economies into two quite different phases: the "wet" and the "dry." The wet phase refers to the rainy season, during which warm, moist, and very disturbed winds blow inland from warm tropical

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[a] A picture of conditions for the tropical Pacific *yesterday* is available at http://www.pmel.noaa.gov/toga-tao/realtime.html. All prediction web sites are given at http://www.atmos.washington.edu/tpop/pop.htm. Various predictions of conditions in the tropical Pacific are provided for next year.

oceans. The dry phase refers to the other half of the year, when winds bring cool, dry air from wintering continents. This distinctive variation of the annual cycle occurs over Asia, Australia, western Africa, and the Americas. In some locations (e.g., the Asia-Australia sector) the dry winter air flows across the equator, picking up moisture from the warm tropical oceans to become the wet monsoon of the summering continent. In this manner the "dry" of the winter monsoon is tied to the "wet" of the summer monsoon and vice versa. In contrast, regions closer to the equator have two rainy seasons. For example, in equatorial East Africa the two rainy seasons occur in March to May and September to December and fall between the two African monsoon circulations. These are referred to as the "long" and "short" rains, respectively.

Agrarian-based societies have developed in the monsoon regions because of the abundant solar radiation and precipitation, the two ingredients for successful agriculture. Agricultural practices have traditionally been tied strictly to the annual cycle. Whereas the regularity of the warm and moist and the cool and dry phases of the monsoon would seem to be ideal for agricultural societies, their regularity makes agriculture very susceptible to small changes in the annual cycle. Small variations in the timing and quantity of rainfall can have significant societal consequences. A weak monsoon year (i.e., with significantly less total rainfall than normal) generally corresponds to low crop yields. A strong monsoon usually produces abundant crops, although too much rainfall may produce devastating floods. In addition to the importance of the strength of the overall monsoon in a particular year, forecasting the onset of the subseasonal variability (e.g., the active periods and the lulls or breaks in between) is of particular importance. A late- or early-onset monsoon or an ill-timed lull in the monsoon rains may have very serious consequences for agriculture, even when mean annual rainfall is normal. As a result, forecasting monsoon variability on timescales ranging from weeks to years is an issue of considerable urgency.

An example of Indian rice yield susceptibility to monsoon variations is provided to illustrate these points. Figure 3.1a plots rice production in India between 1960 and 1996. Figure 3.1b plots the All-India Rainfall Index (AIRI).[5] AIRI is a measure of total summer rainfall over India. The relationship between crop yield and AIRI was first noted in 1988.[6] Figures 3.1a and b provide an updated version of this relationship. In general, rice production has increased linearly during the past few decades. Superimposed on this trend are variations in crop production of about 15 to 20 percent. Some periods of production deficit are associated with El Niño years in the Pacific Ocean (shaded bars), while some abundant years are associated with La Niña, or "cold" events in the Pacific (diagonal bars). Figure 3.2a is a scatter plot of the AIRI and the crop yield as functions of their percent deviations from the mean. The correlation between the two time series is +0.61. All El Niño years (black triangles) fall in the negative quadrant, while all La Niña years (black squares) lie in the positive quadrant. Finally, the relationship between the preceding winter Southern Oscillation Index

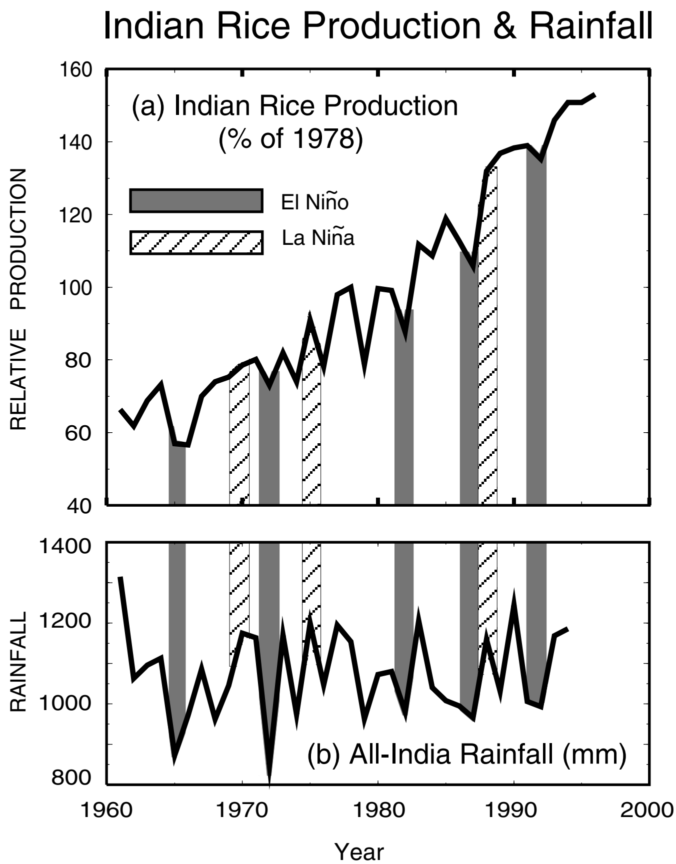
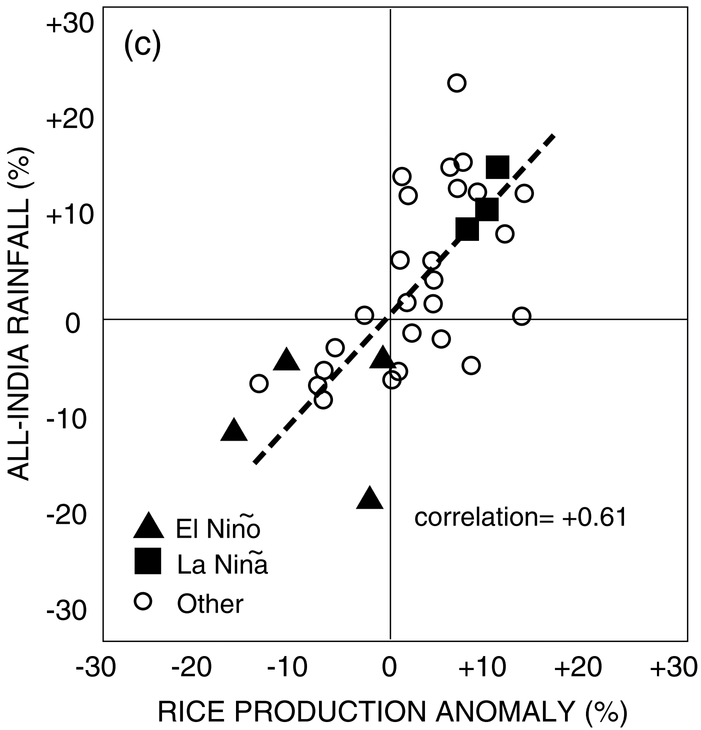


FIGURE 3.1 Relationship of Indian rice production to Indian rainfall. Production in 1978 = 100. SOURCE: Webster et al. (1998); adapted from Gadgil (1995). Courtesy of the American Geophysical Union.

(SOI)—that is, the pressure difference between Tahiti and Darwin, Australia[7]—and the AIRI, is plotted in Figure 3.2b. Generally, warm events in the tropics are associated with deficient rainfall, while cold events appear to be related to abundant rainfall.

The relationship between ENSO conditions and the Indian rice yield suggests a number of questions:

- Although the relationship between ENSO conditions and Indian rice yield is not perfect, it is regular enough to raise the tantalizing suggestion that macroscale variations in the climate system influence variability on the



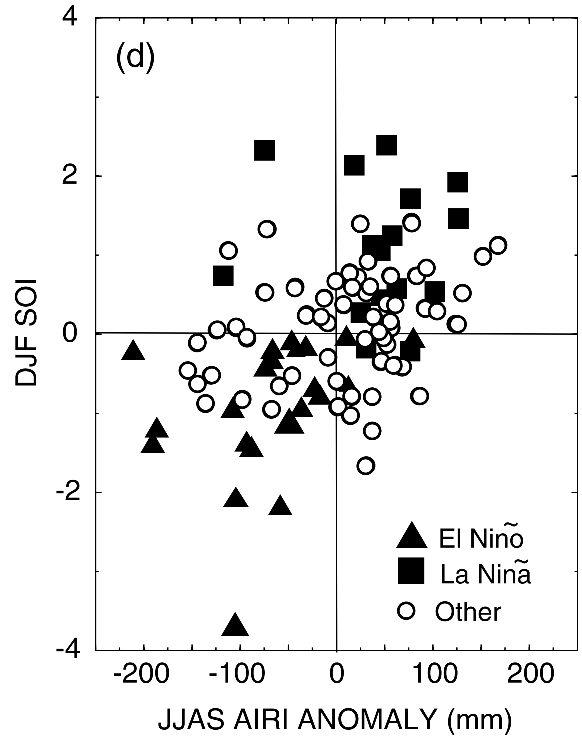


FIGURE 3.2 Scatterplots of (a) AIRI and crop production relationship, depending on their values' percent deviation from the mean, and (b) relationship between AIRI and preceding winter SOI index. (See text for further explanation.) SOURCE: Webster et al. (1998). Courtesy of the American Geophysical Union.

smaller scale of India and South Asia. How is this connection manifested in the physical system?

- Do irregularities in the ENSO/crop yield relationship indicate that intraseasonal rainfall variability (e.g., the timing of the onset and first break of the monsoon in a particular summer, relative to plowing, planting, and harvesting) also influences total crop yield?
- Do the irregularities in the relationship between SOI and AIRI suggest inherent limitations in their linkage? What are the factors involved in any such limitations?
- How accurate must a seasonal forecast of monsoon rainfall be to be of use to the user community? How far in advance would a forecast have to be made?

In the preceding discussion, Indian crop yield is used as an example of the importance of discerning the ways that macroscale climate variability affects the local scale. The questions raised above are common to the monsoon regions of Australia, Africa, and the Americas.

Snow-Monsoon Interactions

In an effort to predict monsoons over a century ago, it was speculated that the varying extent and thickness of Himalayan snow exert some influence on the climatic conditions and weather over the plains of northwest India.[8] Himalayan snow was therefore assessed via snowfall reports from various locations in the western Himalayan range as one of the predictors of Indian monsoon rainfall.[9] Greater winter snowfall was found to be related to below-normal monsoon rainfall for the period 1880 to 1920. However, for the subsequent 30-year period, snowfall was highly variable and its relationship with the monsoon was reversed. Its use as a predictor was dropped.

Since the early 1970s, the Advanced Very High Resolution Radiometer (AVHRR) aboard National Oceanographic and Atmospheric Administration (NOAA) satellites has provided a snow cover dataset that is sufficiently accurate for continental-scale studies. Some pioneering work[10] examined the snow-monsoon relationship using these satellite data. Several observational studies, some examining the role of Eurasian snow extent, others focusing on the Himalayan snow, suggested an inverse snow-monsoon relationship—that is, the less the snowfall, the greater the monsoon.

In the northern hemisphere snow cover ranges from 7 to over 40 percent of the total land area, making it the most rapidly changing natural surface. Snow cover and snow depth in a particular season can be related to atmospheric circulation of the next season through a series of feedback mechanisms.

The two main physical processes through which snow anomalies may affect climate on a seasonal timescale are the albedo effect and the hydrological effect. Excessive snow in the early part of winter tends to reduce solar radiation in winter (up to four times compared to bare ground) by increasing the surface albedo, thus resulting in the persistence of colder temperatures (and possibly additional snow anomalies). Thus, holding other processes constant, excess snowfall gives rise to a positive feedback.

In particular, positive snow anomalies over the Eurasian continent in winter and spring lead to colder ground temperatures in the following summer and hence anomalously weak meridional temperature gradients, because a substantial fraction of the solar energy available in spring and early summer would go to melting the snow and evaporating water from the wet soil. This lower land-ocean temperature contrast would presumably lead to below-normal monsoon. The entire scenario would be reversed when winter and spring Eurasian snows are below normal precipitation.

General circulation modeling sensitivity experiments substantiate observational evidence of an inverse snow-monsoon relationship.[12] In analyzing the relative role of SST variations and land surface processes on the interannual variability of the Asian monsoon system, it is recognized that the former plays a dominant role.

The quasibiennial aspect of monsoons has been investigated, and it has been noted that monsoons play an active role in determining the anomalous state of the warm-water pool in the western Pacific in the following autumn and winter seasons.[13] Studies have also suggested an intriguing three-way interaction between Eurasian snow cover, monsoon, and ENSO.[14]

Forecasting Seasonal to Interannual Variations in Northeast Brazil

The northeastern part of Brazil (in particular, the state of Ceará) is semiarid, has a rainy season from February to April, and is subject to wide rainfall fluctuations from year to year. Throughout Brazilian history, severely dry periods have been marked by severe social dislocations and mass migrations, which have affected the 30 million people of Ceará and the entire social and economic fabric of Brazilian culture.

Statistical correlations of rainfall with climatic indices[15] have indicated that Ceará's rainfall is correlated with SST in both the Atlantic and the eastern Pacific. Realizing the vulnerability of its economy to such interannual climate fluctuations, the state of Ceará, in conjunction with the federal government, established an institute called FUNCEME (Fundação Cearense de Meteorologia e Recursos Hídricos—Ceará's Foundation for Meteorology and Hydrological Resources) to advise the state on the proper actions to take in anticipation of adverse climatic conditions. FUNCEME has published a monthly information bulletin (Monitor Climático) since 1987 that gives monthly global climatic data, ENSO predictions, and local precipitation and hydrological data.

FUNCEME maintains programs addressing both long- and short-term issues. For the long term it advises on actions to be taken on water resources and distribution, well recovery, crop choices and distribution, soil conditions, and environmental degradation. For the short term it issues forecasts for the rainy season and explicit instructions to the various regions of Ceará about the timing of planting and the crops to emphasize, depending on the forecast of abundant or deficient rainfall.

As a result of these activities, the agricultural output of Ceará has gradually grown more stable, no longer subject to the drastic ups and downs of interannual climatic variability.[16] For example, the normal grain output for normal rainfall years in Ceará is 540,000 metric tons. In 1987, before concerted action policies were in place, the response to a poor rainfall year (30 percent below normal) was that grain production for that year was 260,000 metric tons, which led to severe hardship in Ceará and the need for relief by the central governmental. In 1992, however, while the rainfall was equally poor (27 percent below normal), a set of actions in response to a relatively accurate forecast allowed the grain production to be 430,000 tons (see Figure 3.3). Even with a second consecutive very poor rainfall year (again relatively accurately forecast), grain production was 190,000 tons.

Land Surface Factors and Climate Prediction at Less Than Interannual Timescales: The 1993 Mississippi Floods

Terrestrial hydrological-atmospheric coupling processes are reasonably well understood at local scales, and there is increasing understanding on a regional basis. Observational studies and model experiments both suggest that terrestrial hydrological-atmospheric coupling cannot be fully rationalized in terms of local context because the integrated effect of land surface modifies the air prior to its arrival at a specific location.[17]

At the regional scale, some studies suggest that the type of climatic moisture regime prevalent at the beginning of the warm season may be significantly correlated with the subsequent evolution of both temperature and humidity.[18] Early warm season conditions, most likely related to global circulation, can provide the land surface with either more or less moisture relative to the long-term mean. This anomaly may influence subsequent moisture conditions, either locally or regionally, as larger-scale atmospheric circulation becomes less important and local convection (and perhaps moisture recycling) becomes more important in the summer season. Preliminary coupled terrestrial hydrological-atmospheric modeling studies[19] tend to support this hypothesis.

Modeling experiments carried out in the context of the Global Energy Water-Cycle Experiment Continental-Scale International Project (GCIP)—specifically using the Atmospheric Model Inter-Comparison Project's 10-year runs—show that it is possible to provide improved simulation of the mean annual cycle when soil moisture is specified. In practice the soil moisture values used in these runs are estimated from observed temperature and precipitation, rather than from true

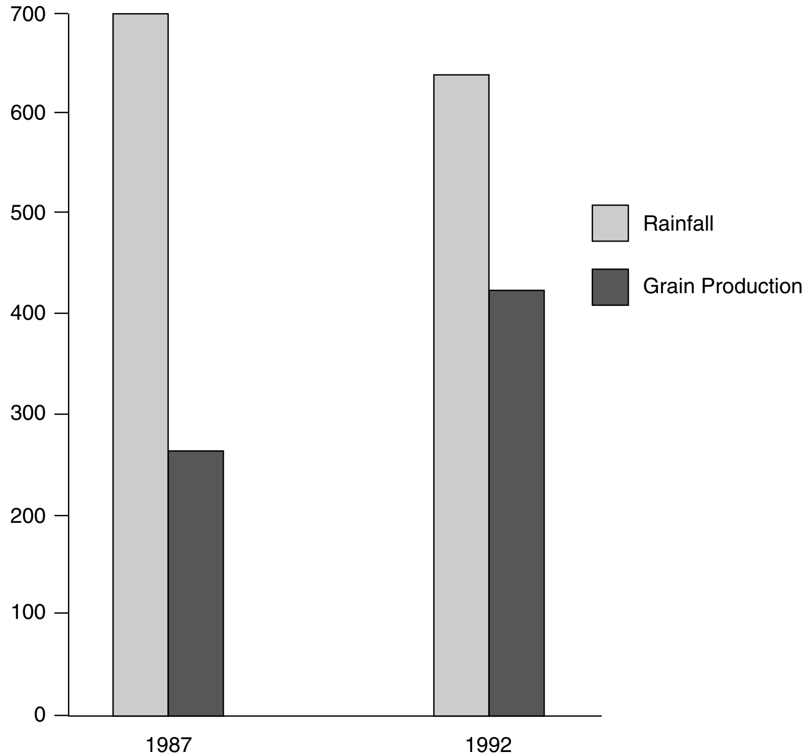


FIGURE 3.3 Grain production (1,000 tons) verses precipitation (millimeters) in Ceará, Northeast Brazil, for 1987 and 1992, both El Niño years. SOURCE: Based on Moura (1994). Data provided by FUNCEME and IBGE/GCEA. Courtesy of the World Meteorological Organization.

soil moisture measurements. Nonetheless, these AMIP simulations suggest that improved specification of soil moisture, and, it might therefore be presumed, improved prediction of the seasonal evolution of soil moisture in coupled terrestrial hydrological-atmospheric models, have the potential to improve seasonal precipitation forecasts.

Dynamical processes controlled by regional water and energy balance can influence vapor flow and in this way may contribute to the occurrence of extreme events. The control of land surface processes primarily arises through their effect on the Bowen ratio, which influences the diurnal evolution of the boundary layer. Land surface processes also have substantial influence on elevated mixed layers and on associated “lids” on atmospheric instability that focus the release of convective instability and hence determine the distribution of regional precipitation in time and space.[20]

A particularly important issue regarding North America is that the surface energy balance is known to affect the low-level jet over the Great Plains. Such coupling has been demonstrated by numerical modeling and from observations.[21] This low-level jet is, in turn, a major factor in the regional moisture transport and moisture flux divergence in the Mississippi River region.[22]

The case of the 1993 floods in the Midwest is particularly revealing. Simulations carried out at the European Centre for Medium-Range Weather Forecasting (ECMWF) used two land surface schemes—one with known defects and another with model improvements correcting those defects such that regional-scale soil moisture fields were better represented in the model.[23] Predictions made with the version that more poorly represented surface interactions, and thus calculated overly dry soil moisture, provided an unrealistic simulation of the 1993 Mississippi River floods. However, simulations made with the improved representation of surface processes gave a much improved simulation of the persistent rain that caused catastrophic floods and extensive damage in the central Mississippi during July 1993. One study[24] concluded, converse to other conclusions,[25] that upstream moistening would lead to a weakening of the low-level jet and so act to reduce Mississippi flooding, A follow-up study[26] found that changes in the low-level jet were sensitive to a limited-area model's lateral boundary conditions and that such changes would largely vanish with a large-enough domain.

A RESEARCH AGENDA FOR THE NEXT DECADE

Research Imperatives and Key Scientific Questions

There are five Research Imperatives in studying climate on seasonal to interannual timescales:

- *ENSO*. Maintain and improve the capability to make ENSO predictions.
- *Global monsoon*. Define global seasonal to interannual variability, especially the global monsoon systems, and understand the extent to which it is predictable.
- *Land surface exchanges*. Understand the roles of land surface energy and water exchanges and their correct representation in models for seasonal to interannual prediction.
- *Downscaling*. Improve the ability to interpret the effects of large-scale climate variability on a local scale (downscale).
- *Terrestrial hydrology*. Understand the seasonal to interannual factors that influence land surface manifestations of the hydrological cycle, such as floods, droughts, and other extreme weather.

ENSO Imperative

Dynamical climate predictions began with a 1986 forecast[27] and ever since have increased in skill and proven valuable in applications around the Pacific basin and in other regions where ENSO exerts strong control. The field is relatively young, standing roughly at the same place numerical weather prediction did after an initial crude forecast in 1948.[28] Coupled models are being developed, data assimilation techniques are being implemented and tested, and various schemes are being used to teleconnect the forecasts of SST to midlatitudes. Forecast systems for the United States are being developed by the National Center for Environmental Prediction, and the concept of end-to-end forecasting is being demonstrated by the newly formed International Research Institute for Climate Prediction. The need now is to proceed.

The following questions are essential to address for progress in ENSO forecasting:

What is the inherent limit of ENSO predictability? How can this limit be determined? What limits the skill of ENSO predictions now? Relatively skillful forecasts of SST in the tropical Pacific are now being made at lead times of one year, with indications of predictive skill for up to two years in advance.[29] It is of great interest to know if there is an ultimate limit to predictability in the same way that deterministic prediction of weather is inherently limited to the order of two weeks or so. The limitation is given by how fast errors grow, and this limit can be investigated by examining error growth in models under various circumstances.[30] Performing regular and systematic forecasts is another way of gaining experience with predictability limits, since the inherent limit cannot be less than the skill actually attained. Current forecasts are presumably not near this inherent limit, so it is important to know what constrains current prediction schemes—such as model errors, inadequate data, inaccurate data, or incomplete physical parameterizations.

What mix of observations is needed to initialize forecasts to optimize the skill of ENSO predictions? How can this mix be determined? A prediction must be initialized with the proper state of the coupled atmosphere-ocean system. Currently available data include the TAO array, historical winds from the Comprehensive Ocean-Atmosphere Dataset, sea-level height from altimetry and island stations, subsurface data from expendable bathythermographs, and others. The system has not been "designed" in any sense, so it is possible that a rearrangement of, say, the TAO array could increase skill, as might adding additional moorings or spending more money on some part of the observational system at the expense of others. These questions can be answered in models by performing Observing System Simulation Experiments, in which known model results are subsampled at the observational system points with comparable accuracies. The best observational system maximizes skill.

Which are the proper measures of the skill of ENSO prediction? Current measures of skill are in terms of single indices, in particular NINO3, which is the averaged SST from 5°S to 5°N and from 90°W to 160°E. The correlation of this predicted index with observed and root mean square difference between predicted and observed values of this index, as compared to persistence, is the basis of current skill scores. This definition of skill is oversimplified, but a more acceptable skill score has not yet been developed.

How does decadal variability in the Pacific affect the prediction of ENSO? Long series of hindcasts have shown that skill is not stationary—it varies from decade to decade.[31] The persistence skill itself varies decadally. Recent discoveries of decadal modes in the Pacific[32] raise the question of whether the decadal variation of skill can be related to physical modes of decadal variability.

Through what mechanisms do seasonal to interannual tropical Pacific variations influence the midlatitudes? It has been known from inferences about the remote effects of ENSO and from modeling studies that SST in the tropical Pacific affects midlatitude regions.[33] To develop skill at midlatitudes, it is important to accurately model these remote effects.

What is the relationship between the annual cycle and ENSO predictability? Do models have to get the annual cycle right to predict ENSO correctly? Is there a predictability barrier? The annual cycle is the most reliable and important climatic signal, yet it is not well understood in the tropics. In particular, coupled general circulation models (GCMs) have had enormous trouble getting the annual cycle correct, and this has slowed progress on prediction. On the other hand, the relationship between the annual cycle and ENSO and its prediction are still areas of active research. Early results seemed to indicate that prediction skill dropped off radically during the spring months, but more recent predictions seem to have gotten through the first spring with little loss of skill.

What is the effect of regions outside the tropical Pacific on the prediction of ENSO variations? The simpler models (e.g., the Cane-Zebiak model) include only the Pacific basin yet still manage to attain high skill scores. Some evidence suggests that there are correlations between the Asian monsoon and ENSO and between Atlantic climate and ENSO. Whether these correlations mean that the connections to other basins must be taken into account in predicting ENSO, or whether they are just the remote effects of ENSO, is still not known.

Global Monsoon Imperative

The first question that must be faced in addressing this Research Imperative is the following: *What are the structure and dynamics of the annual cycle of the coupled ocean-atmosphere land system, and what are the reasons for its large spatial variability over the globe?* The seasonal to interannual variabilities of climate are relatively small fluctuations of the predominant and largest amplitude of all climate variations: the annual cycle. For example, a modest shift in the wintertime planetary wave configuration can bring below-average and more frequent snowstorms to the United States. A small displacement of the convection associated with the summer monsoon can bring floods or droughts to the semiarid regions that lie along the margins of the monsoon rain belts. Thus, to predict the climate anomaly patterns as they evolve from one season to the next requires a thorough understanding of the annual cycle and an ability to model it. However, the annual cycle is strikingly different in different parts of the world. Phase relationships between the annual cycle and solar radiation are highly variable. Furthermore, the amplitude of the annual cycle in different parts of the globe is very different. The differences in phase and amplitude are caused by different responses of the atmosphere, ocean, and land to thermodynamical forcing and the regional dynamical responses of the coupled system to this forcing.

To date, we can describe the gross features of the coupled ocean-atmosphere-land system, yet we are not so well advanced in modeling this variability. For example, simulating the phase of the annual SST in the Pacific Ocean is still elusive. But to forecast small deviations from the annual cycle, it must be keenly modeled.

What is the nature of global interannual climate variability, and what is its relationship to the annual cycle? What processes give rise to such variability? Can our increased understanding of this variability be exploited for prediction? The ENSO cycle is the dominant mode of interannual variability in and over the Pacific Ocean. The TOGA program has established that ENSO variability is the result of coupled ocean atmosphere processes. Additionally, the ENSO cycle is phase locked with the annual cycle, although there is recent evidence that this locking tends to shift on interdecadal timescales. Rather robust theories have been developed to explain the coupled ocean-atmosphere dynamics that produce ENSO, but why ENSO is phase locked at all with the annual cycle is less well known. It has long been established that there is interannual variability in other parts of the globe, especially in the monsoon regions. Some of this variability appears to be connected to ENSO. It is not known, however, whether there are other large-scale forcing functions (e.g., variations in ground moisture, winter snow cover) or whether there is a chaotic component to the monsoon. Clearly, though, advances in predicting interannual variability must begin with a more thorough description and understanding of the climate system.

What are the roles of slowly varying conditions at the Earth's surface (sea ice, SST, snow cover, and soil moisture) in determining the nature of interannual variations in the global atmosphere? It has been hypothesized that in the extratropics there is little predictability beyond a few weeks because the circulations are dominated by short-term hydrodynamical instabilities, which, from a climate perspective, are essentially unpredictable. It is generally believed that in the tropics, there are no hydrodynamical equivalents to baroclinic instabilities. Thus, it has been hypothesized that the interannual variability of the tropics should be determined by the slowly varying boundary conditions, especially the SST variations associated with ENSO. To a large degree this appears to be a robust result. Yet in the monsoon regions there is some evidence of dynamically unstable modes. Whether such modes reduce the predictability of the monsoon has not yet been determined.

In the continental regions of the higher latitudes (e.g., the United States), anomalies in soil moisture can persist for periods longer than a season. At higher latitudes there are long-lived sea ice and snow cover anomalies as well. Whether these extratropical anomalies can nudge the chaotic dynamics to some preferred state, and thus add predictability to the system, has yet to be determined.

What determines the low-level convergence of moisture in the tropics over water, land, and coasts? More generally, what determines the location and longevity of the heat sources and sinks of the atmosphere? The heating gradients between the heat sources and sinks of the atmosphere determine the basic circulation characteristics of the coupled climate system. Heat sources are generally related to regions of latent heat release and are usually located over the warm tropical oceans or tropical land areas. Heat sinks are associated with radiative loss to space. The subtropical continental desert regions and the subtropical high-pressure regimes over the oceans are heat sinks. The greatest and most persistent heat sink exists over North Africa and the Middle East. The heat sources are formed in a cooperative manner. It is thought that the convergence of moisture is caused by surface heating of the atmosphere either over the tropical ocean warm pools or the heated continents. The release of latent heat in these regions defines the heat source. During the year, the heat sources tend to migrate following the Sun but with different rates of progression depending on their relationship with the ocean or the land. We are fairly certain that major heat sources and sinks are not independent, and it appears that they interact. But how they interact and modify one another is not known. Nor is it known how these interactions produce rainfall anomalies, which are often on scales that are less than the scale of the sources.

What is the role of ENSO in creating variability in the monsoon climates of the world and vice versa? For over 100 years it has been apparent that the Asian-Australian monsoon system undergoes aperiodic and high-amplitude variations. Often (but not always) the monsoon variability appears to move in synchronization with interannual ENSO variability in the Pacific Ocean. At other times there appears to be only a weak relationship or none at all; at still other times monsoon variability appears to lead ENSO. These associations between ENSO and the monsoon are real but exactly how the two systems relate physically is still not fully understood.

Is there variability of the monsoon that is independent of ENSO and is it predictable? The Southern Osilation Index (SOI) explains about 45 percent of the variance of the Indian summer rainfall. Clearly, other factors must be important. One possibility is the snowfall over Eurasia during the previous winter and spring. If there is abundant snowfall, the ground surface processes are affected, so that warming of the Asian continent is retarded. Possibly this leads to slow formation of the monsoon trough over India. There are SST anomalies in the Indian Ocean although they are usually a factor of two smaller than those found in the Pacific Ocean associated with ENSO. However, the impact of these anomalies has not been fully explored, especially as they relate to regional aspects of the monsoon. Possibly, there may be an unpredictable component in the monsoon structure. In this theory the SST anomalies associated with ENSO control the macroscale monsoon to a large degree, tending to render the monsoon anomalously wet or dry. However, hydrodynamical instabilities in the monsoon system (if they exist) would add an unpredictable element to this large-scale control. At this time the role of such boundary forcing factors or the introduction of such uncertainty into predictions of the monsoon system is not understood.

What is the nature of tropical-extratropical interactions? Specifically, how might tropical SSTs perturb the extratropical atmosphere, thereby generating extratropical SST anomalies? For what regions of the globe can accurate predictions of tropical SSTs be translated into skillful regional climate forecasts for one to two seasons in advance? The general view is that, compared to the tropics, there is little if any predictability inherent in the extratropical system on seasonal to interannual timescales. The predictability that does exist at higher latitudes results from the atmospheric response to tropical SST anomalies that exert their influence through teleconnection patterns. Extratropical SST anomalies appear to be forced by these patterns. In turn, the extratropics can exert a stochastic forcing on the more predictable tropics. How much tropical predictability may be reduced by this influence is unknown.

What is the role of intraseasonal variability on seasonal to interannual variability? How predictable are the amplitude, distribution, and frequency of blocking, and active and break periods of the monsoon? Intraseasonal variability is an important element of tropical and extratropical climates. For example, active and break periods of the monsoon produce variability in rainfall on timescales of 10 to 30 days. Timing within the monsoon climate is critical, as even in a good monsoon year an "ill-timed" break can have devastating consequences. Blocking at higher latitudes modulates weather for long periods of time. Yet the physical processes that produce intraseasonal variability have not been identified. Nor are these processes simulated or predicted with sufficient accuracy in numerical models. The manner in which intraseasonal variability affects seasonal to interannual variability, or vice versa, also is unknown.

Land Surface Exchanges Imperative

Five general Scientific Questions need to be explored to investigate land surface processes involving energy and water:

What is the appropriate level of detail in characterizing land surface for *seasonal to interannual prediction, with regard to (1) the nature of vegetation and soil parameters and their specification, (2) the spatial resolution in observing vegetation and soil, and (3) description of seasonal changes in vegetation cover and its vigor?* Vegetation influences several aspects of the hydrological cycle. There is long-standing evidence that vegetation cover affects catchment runoff, and the interception of rainwater by canopies and its rapid reevaporation are recognized as important in this. Foliage is known to exert biological control on transpiration by regulating the stomatal pores through which water vapor leaves a plant. The morphology of plant canopies also influences the absorption of solar energy and the generation of turbulence. These factors together influence the energy balance between radiant energy, sensible heat and latent heat, and heat flow in the soil. The sensitivity of stomata to soil moisture change is small when soil moisture is high but is a strong control on transpiration when soil moisture is low.

The nature of the underlying soil is also important to land surface hydrological-atmospheric coupling. Infiltration of water in the soil surface (which can be modified by root growth and soil tillage) influences how much precipitation enters the soil and how much runs off to river systems. Soil parameters in the vegetation rooting zone determine the amount of water that can be released to the atmosphere during a long dry period and how much water percolates to groundwater.

Modern biosphere-atmosphere models can simulate complex soil-vegetation-atmosphere interactions realistically, and model sensitivity studies confirm that realistic description is indeed necessary when simulating climate over decades and longer. It is not yet clear what level of realism is appropriate for seasonal to interannual climate prediction. Climate models adopt alternative approaches when specifying vegetation and soil parameters. Some models assign values according to the nature of the local land cover ascribed to areas in globally specified land cover maps, while others specify the value of individual parameters globally. The relative merits of these two alternative approaches for seasonal to interannual prediction also are not known.

Over the past decade, substantial progress has been made in understanding how to represent subgrid-scale heterogeneous land cover and thus representation of surface energy partitioning in climate models for long-term prediction. Meanwhile, rapid progress has also been made in obtaining remotely sensed land cover data to apply that understanding. No attempt has yet been made to apply this knowledge at seasonal to interannual timescales.

To operate, biosphere-atmosphere models must be supplied with or generate information on leaf area and its seasonal development. Model experiments reveal that predictions are sensitive to vegetation type and cover. Currently, seasonal to interannual predictions must assume specified seasonal behavior for these variables, but models that simulate seasonal growth and senescence may be preferable.

What representation of runoff is best to calculate evapotranspiration in seasonal to interannual climate prediction models? Models used for seasonal to interannual prediction must simulate surface water balance realistically to calculate the seasonal evolution of evapotranspiration accurately. To model surface water balance well, they must provide appropriate descriptions of runoff processes. However, in the past, climate models have paid meager attention to representing this aspect of the land surface hydrological cycle, and greater emphasis must be given to modeling runoff in coupled hydrological-atmospheric models, and to validating the modeled runoff against observations.

What is the appropriate form for the land component of a four-dimensional data assimilation system for seasonal to interannual prediction? What are the appropriate measurements and tradeoffs? How can they be obtained and how can models be formulated to accept them? It is more important that seasonal to interannual climate models are accurately initiated, as compared to longer-term prediction models. Correct initiation of state variables in hydrological-atmospheric models is thus important, while initiation of soil moisture status in such models is critical. In this regard there is potential value in using four-dimensional data assimilation procedures to initiate models, when using observations of near-surface soil moisture from spaceborne L-band[b] radiometers. Meanwhile, model-calculated soil moisture fields must be used in initiation, seeking improvements in them by improving the realism of the model and the reliability of the model inputs used in the calculation.

How can we use observations of seasonal to interannual variations in biogeochemical cycles and ecosystem properties to infer the underlying dynamics determining these variations? Over the past decade, noteworthy progress has been made in using networks of in situ concentration measurements to determine the location and seasonality of trace gases in the global atmosphere and in using remotely sensed data as an indirect measure of seasonal variations in ecosystem properties. These integrating measurements have potential value in validating the representation of seasonal features in ecohydrological models.

What is the role of high-latitude feedbacks between snow cover extent, streamflow, and seasonal to interannual variability and to what extent are these processes adequately modeled? The extent of snow and ice varies markedly from year to year, which can have a major impact on the global radiation budget because of the associated change in the surface reflectivity for solar radiation. At high latitudes and high altitudes, surface water stored as snow and ice during the winter season is released as streamflow, to return to oceans in the subsequent spring and summer, thus providing a means for achieving freshwater balance between seasons. The presence of an energy-related storage mechanism in the Earth's water budget provides opportunity for seasonal feedback, which may be poorly modeled in predictive models.

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[b] The L-band is the nominal frequency range from 2 to 7 Gh_z (20 to 76 cm wavelength) within the microwave (radar) portion of the electromagnetic spectrum.

Downscaling Research Imperative

Downscaling—interpreting the effects of large-scale climate variability at the local scale—lies at the heart of meeting users' requirements. For successful downscaling, two key questions must be resolved.

In what ways can local climate variance be explained in terms of large-scale climate variability? Transformation of large-scale GCM climate predictions to regional and local areas is critical to interdisciplinary scientists and others who wish to know the impacts of climate variability on their areas and activities (e.g., water resources, agriculture, urban development). As already noted, the influence of many factors, such as topography and land cover, determines whether any change predicted at a typical GCM grid size projects down to local land surface scales in a linear way. Three methods have been used to address this issue. The first approach is the empirical and statistical method, called a Weather Generator, which derives a correlation between a specific local climate variable (such as precipitation) and an appropriate measure of large-scale climate variability (such as the height of a 500-mb pressure surface). The availability of reasonably long historical records of the variables is essential to this approach. The second approach is a dynamic method of nested modeling, which increases the spatial resolution for the study region in a GCM. A third approach is to use a nested regional model that is forced at its boundary by GCM results. Each approach estimates changes in the local climate variance that are related to large-scale (GCM-scale) climate variability.

Current methods rely on additional scaling knowledge, either from observation or dynamics, to complete the transformation. Therefore, any enhancement of these methods will require improved descriptions of related physical processes at high resolution and through the use of remote sensing data.

The second question deals with "upscaling" local variables for use in large-scale models: *What local climate variables need to be upscaled to ensure adequate coupling of local climate to large-scale climate?* Although the role of land surface in the climate system was always thought to be important, until recently most atmospheric modelers believed that it played only a minor role in influencing climate variability. New research reported in connection with the GCIP program has changed this perception. Recent improvements in the new ECMWF model, in simulating the heavy 1993 rainfall over the upper Mississippi River basin, have been attributed to the use of a new land surface scheme;[34] this has helped to increase the GCM modeling community's interest in the potential influences of the land surface. The recent emphasis on improving land surface parameterization (LSP) schemes is a move in the right direction. However, there are still many unresolved problems with LSPs. A major problem is related to the horizontal subgrid parameterization of processes that control surface energy and water fluxes. The current generation of LSPs use a point or patch representation of the land surface, with effective parameters, at the mesoscale or GCM grid scale. All the heterogeneity of the land surface is assumed to be subsumed into these effective parameters. The most immediate consequence of this assumption is the implication that runoff production is linear with scale. This is clearly not the case, given that only parts of the land surface are responsible for runoff production. It is therefore critical that the effects of heterogeneity in inputs, soil characteristics, and antecedent moisture be appropriately represented in LSPs, so that adequate coupling of local climate to large-scale systems can be established. A reasonable description of runoff, to allow direct GCM simulations of climate variability effects on river discharge, will be critical to the hydrological and water resources communities.

The horizontal heterogeneity discussed above also influences and is influenced by the vertical mechanisms of the transport of energy, water mass, and momentum from the Earth's surface to the lower boundary of the atmosphere known as the planetary boundary layer (PBL). The vertical transfer mechanisms between the land and the PBL occur at spatial resolutions much finer than the typical GCM grids.[35] Relatively minor improvements in the PBL models and parameterization have been made to date. Additional research focused on PBL transport response to land surface variations will most likely provide the critical insight needed to improve LSPs and hence the coupling of local to large-scale climate.

Terrestrial Hydrology Imperative

Seasonal to interannual forecasts of hydrologically important surface variables (especially precipitation and temperature) could be incorporated into hydrological forecasts (in particular of streamflow), which in turn could have important benefits for water managers. However, important Research Questions remain in making the transition from surface climate to hydrology. These questions reflect mismatches in spatial scale and the sensitivity of predictions of the hydrological system to even modest biases in surface climate forecasts. These research questions include the following:

What are the implications of seasonal to interannual climate forecasts for flood prediction? Opportunities exist in several areas. With respect to flash floods (the severity of which is usually controlled by the intensity of precipitation over relatively small watersheds), there is potential for predicting changes in flood risk (e.g., the magnitude of the *n*-year flood) depending on the current (or forecast) climate state. This capability is distinguished from the forecasting of particular flood events at seasonal to interannual timescales, which is unlikely to be feasible for the foreseeable future. Likewise, it may be possible to predict the risk of rain-on-snow floods in the maritime mountainous environments of the western United States, although prediction of specific events at seasonal to interannual timescales is unlikely to be feasible. On the other hand, for floods in large continental river basins, it may be possible to predict the evolution and timing of specific flood events. This is particularly true for situations in which antecedent conditions (such as soil moisture and snow moisture storage) exert a strong influence on future runoff. The skill of climate forecasts should be evaluated with respect to precipitation, including statistical descriptors of its space-time evolution. Similarly, for spring snowmelt floods in the mountainous west, forecasts of winter precipitation and temperature might be used in conjunction with hydrological models to predict the evolution of spring snowmelt. But important questions still remain about the ability of climate models to predict the coincident evolution of precipitation and temperature that controls the buildup of the winter snowpack.

What are the implications of seasonal to interannual climate forecasts for drought prediction and forecasting? Three kinds of drought can be distinguished. *Meteorological drought* can be specified in terms of accumulated precipitation anomalies. Therefore, the value of seasonal to interannual climate forecasts for predicting meteorological drought is directly related to their skill in forecasting precipitation. *Agricultural drought* is defined in terms of soil moisture deficit (e.g., from field capacity), which is related to the accumulated difference between precipitation and evapotranspiration. Therefore, agricultural drought is determined by a more complex interaction of evaporative demand (which in turn is a function of net radiation, wind speed, and vapor pressure deficit) with precipitation and initial soil moisture. Hydrological drought is defined in terms of streamflow (perhaps averaged over an appropriate time period). Hydrological drought is governed by variables similar to those of meteorological drought, but they interact in a more complex manner. For instance, streamflow is conceptualized in many models to be derived from two sources: surface runoff production, which is related to instantaneous precipitation intensity and local surface soil moisture, and drainage, which is defined over longer timescales by soil moisture (and/or groundwater) at depth. Under drought conditions, drainage (manifested as baseflow, which is primarily the groundwater contribution to streamflow) dominates. Therefore, hydrological drought is determined by the complex interaction of processes that lead to deep soil moisture, and/or groundwater characteristics, throughout the forecast period.

What are the implications of seasonal to interannual climate forecasts under "normal" climate conditions? Seasonal to interannual forecasts may offer considerable benefits for improved water-use efficiency under "normal" conditions. Especially in the western United States, where streamflow is fully appropriated, water management issues almost always exist, not just during extreme years. For instance, in streams where water rights are fully appropriated (as in much of the western United States), junior water users are not entitled to irrigation water until senior users have been satisfied. Therefore, these users could benefit from more accurate information about streamflow at seasonal to interannual lead times, which may determine whether, and what, crops are planted. Likewise, hydroelectric power operations are critically dependent on information about future streamflows because the value of the power generated depends on how far in advance contractual commitments can be made for power delivery. Navigation, recreation, and environmental activities (including fisheries protection and enhancement) could also enjoy economic and other gains, if future information about streamflow (and/or reservoir releases) were available. Methods of using seasonal to interannual climate forecasts under these conditions may well have greater long-term economic benefit than forecasts under less frequent flood or drought situations.

LESSONS LEARNED

Four central lessons emerge from experience with TOGA and with ENSO prediction.

1. A close relationship between models and observations is the clearest way to progress. One of the key lessons learned from the TOGA program was the fruitful and reinforcing relationship between models and observations. It showed that a balanced approach to modeling and observations was the surest way to progress and that both observations without models and models without observations were inadequate.

Linear models of the response of the equatorial thermocline to winds were worked out by the early 1980s, allowing quantitative tests of the theory, something really quite new in oceanography. Measurements of the thermal structure of the equatorial ocean were taken, yielding a good indication that the large-scale structure of the thermocline could be understood in terms of the large-scale structure of the winds.[36]

The development of ENSO prediction also forced a fruitful confrontation between models and observations: observations were absolutely required to initialize the predictions, and the constant need to evaluate the predictions' accuracy required constant comparisons of the model to the verifying observations. Initialization required assimilating data in the model, and this demanded that the model be good enough to accept the data; if not, the data require that the model and/or assimilation procedure be improved. Once the model is good enough to assimilate the data, the initial analysis gives a view of the system that would be impossible from the data alone. The case is much like weather prediction, except that ocean data were essential to initialize the forecasts, and fields of ocean model-assimilated data are the products of the analysis procedure.

2. The ocean and land are woefully undersampled, with resulting major lacunae in understanding, simulation, and prediction. There are many parts of the deep ocean where no instrument has ever recorded an observation. Even at the surface, some parts of the Southern Ocean have never been sampled. The equatorial Pacific is only sparsely traveled by volunteer observing ships. Thus, the long-term surface database (COADS—Comprehensive Ocean-Atmosphere

Dataset) did not allow complete study of surface interannual variability over the ENSO region. The research community depended instead on interpolated wind fields from relatively sparse sampling (in time and space) to force the ocean models. Fortunately, the large-scale behavior of the ocean could be described by relatively crude wind fields, so that progress was delayed but not short-circuited altogether. The demands of prediction, however, require a better dataset: it was not until the establishment of the TOGA TAO array that the surface meteorology became better established.

Lacking a long-term dataset in and over the ocean means that the variability of SST, both interannual and on longer scales, remains unknown over large reaches of the ocean. It is just such a lacuna that the U.S. Global Ocean-Atmosphere-Land Surface (GOALS) program is designed to address. The current combination of satellite and in situ measurements, if maintained both continuously and permanently, will lead to a global SST dataset with few gaps. Because the satellites that provide SST are routinely used in weather prediction, the likelihood that this will happen is good. For other surface quantities, such as wind or sea-level height, the prospects are not as good. Such measurements are extremely valuable, but they are not in the operational domain, so there is no requirement (or intention) that they be permanently maintained. In fact, no institution is responsible for long-term measurements outside the domain of weather prediction, no matter how valuable these measurements may be for the climate record.

For measurements beneath the surface of the ocean, the situation is rather bleak. At only two isolated sites in the ocean are long-term (point) measurements taken, from the weather ship Mike (in the Norwegian Sea) and the Bermuda station. The TAO array is the first measurement system deployed in the world's oceans that is designed to permanently measure quantities of vital interest to the prediction community and by extension to the oceanographic community. How to maintain the TAO array when no operational agency has responsibility for it is a problem that has occupied the research community in seasonal to interannual prediction for several years.[37] The problem is in fact generic: no operational agency supports any measurements other than those taken for weather prediction.

3. Scientists from different fields work together most productively and smoothly when the problem demands it—and global change demands it. There is much talk about the value of interdisciplinary studies, but it has proven difficult to encourage people in different fields to work together. In global change research, however, people from entirely different fields, such as meteorology and oceanography, have worked together smoothly and without prompting because the problem requires their cooperation. The ongoing work on ENSO shows this to be the case. The relatively few people who work between fields, and who show that multiple fields are sometimes essential to find solutions, are the true innovators of interdisciplinary studies.

The decadal climate problem is the kind of problem that demands expertise in a wide variety of fields. A climate model must have land, ocean, atmosphere, and cryosphere components. Chemical processes must also be encompassed to determine such features as the concentrations of major constituents and the radiative properties of gases, aerosols, and clouds. Land processes expertise is needed as well to characterize the vegetative cover and the marine biological processes that determine the uptake and sequestration of CO_2. Thus, the modeler must be a master of all trades.

Similarly the study of ENSO requires knowledge of the convective properties of the atmosphere and how surface winds are generated and altered. It has required understanding of the response of the ocean to such atmospheric changes in terms of thermocline depth changes and, in general, understanding of the interaction of the atmosphere and the ocean in affecting SST.

The lesson is that, wherever barriers are raised, ways must be found to enable people who wish to collaborate with those in other fields in solving specific problems to work together. This may involve more than physical scientists working together—the application of seasonal to interannual prediction requires physical and social scientists to collaborate. The barriers to such collaboration exist in universities, government, and funding agencies.

4. Systems of interest (e.g., agriculture, fisheries, water management) are physical, political, and social; such systems must be studied in both physical and human dimensions. To use seasonal to interannual climate forecasts to our advantage, the identification of applications and the methods of using and communicating the forecasts must be carefully researched. In doing this it is vital to realize that most systems we intend to benefit can only be understood in terms of their normal workings.

The simplest systems are not nearly as simple as is usually assumed. Agriculture depends not only on seeds, sunlight, and water but also price supports, capital availability, opportunities for alternative work nearby, the technological sophistication of the farmer (including knowledge of new varieties and hybrids of seeds and animals), the existence of cooperatives, the care with which the farmer has tended the land, communications of weather and climate information, availability of educational facilities nearby, accessibility of pest control weapons—and still other factors. Agriculture has clear human dimensions that must be understood.

RESEARCH IMPERATIVES: PRIORITIES FOR OBSERVATIONS, MODELING, AND THEORY

Earlier we identified five Research Imperatives that must guide the next decades of research into the interannual timescales of the climate system:

- *ENSO.* Maintain and improve the capability to make ENSO predictions.

- *Global monsoon.* Define and predict global seasonal to interannual variability, especially the global monsoon systems.
- *Land surface exchanges.* Understand the roles of land surface energy and water exchanges and their correct representation in models for seasonal to interannual prediction.
- *Downscaling.* Improve the ability to interpret the effects of large-scale climate variability on a local scale (downscale).
- *Terrestrial hydrology.* Understand the seasonal to interannual factors that influence land surface manifestations of the hydrological cycle, such as floods, droughts, and other extreme weather.

ENSO Research Imperative

The development of short-range (seasonal to interannual) climate prediction during TOGA has opened the doors to a new age of possibilities. It is not hard to imagine short-range climate prediction finding its place in the economic apparatus of modern industrial society, by providing valuable information about the future that can be used to economic advantage. Short-range climate prediction for the United States is in its infancy but through careful nurturing could be brought to maturity.

The key to developing better forecasts is a balanced combination of modeling, observations, and continuing research. It is absolutely essential to maintain the TAO array and other tropical Pacific observing systems until their value can be more carefully assessed, with reference to the objective standard of skill in prediction. Also crucial are continuing efforts to develop "end-to-end" prediction, in which predictions are not only made but used, evaluated, and improved, and the applications of the predictions also pass through such developmental stages. Additionally, demonstration projects are needed to learn how forecasts are used and how to increase their effectiveness. These demonstration projects do not have to be focused on the United States; they could initially be carried out in regions for which predictive skill is higher, particularly in countries around the tropical Pacific. The newly formed International Research Institute for Climate Prediction should be encouraged to develop these demonstration projects. Finally, commitment to the Program for Climate Variability and Predictability (CLIVAR)/GOALS and the Global Energy and Water Cycle Experiment will assure that the research needed to advance seasonal to interannual climate prediction will be done.

Observational Requirements

The ENSO prediction process—predicting aspects of SST and corollary variables—requires data to initialize the coupled models and data to evaluate the skill of the predictions. Because SST is the crucial variable in making predictions, weekly fields of SST at the one degree by one degree level are absolutely essential. These are currently provided by AVHRR measurements, combined with in situ drifters to pin down the absolute values and gradients of SST. The key variables for initializing the model are the state of the atmosphere and the density state of the upper ocean. The state of the atmosphere does not seem to be as critical for initialization, since the model atmospheric state rapidly adjusts to the initial SST. In any case, the state of the atmosphere is provided by the twice-daily analyses from the operational weather prediction models.

The internal state of the upper ocean can be assessed in two separate ways: directly by temperature-measuring instruments, on a line connecting a surface mooring to a bottom anchor, or indirectly by applying observed heat and momentum fluxes over the ocean component of the coupled model for a long period of time (usually exceeding 20 years). In practice, salinity is very difficult to measure and does not make a major contribution to the initial thermal state, so the direct method measures only temperature. The indirect method depends primarily on measuring the momentum fluxes with the heat fluxes parameterized, so that only the surface winds are used in the calculation.

Currently, ocean models are initialized by combining the two methods above, by assimilating both the long-term history of the wind fields and the currently obtained thermal state of the upper ocean, to arrive at an optimal estimate of the ocean's current thermal state. The subsurface ocean data are provided by a network of 70 moored TAO arrays in the tropical Pacific Ocean (providing approximately 2 degrees of meridional resolution and 15 degrees of longitudinal resolution). These same moorings measure winds, but, since the full TAO array has been in existence for only two years or so, historical winds must be obtained from the COADS dataset, gathered from individual ship reports from volunteer observing ships.

Because the TAO array measures the quantities needed to initialize the ocean component of the predictions, it is vital that this array be continued. The TAO array was designed on the basis of the scales of variability of the winds. It may turn out that either fewer or more moorings are required to optimize prediction skill. Other quantities also prove useful for initialization:

- Sea surface height, as measured by satellite altimetry and by tide gauge stations scattered around the islands and coasts of the tropical Pacific.
- Currents measured on the equator, where geostrophy is more problematic.
- Cloud cover and solar irradiance reaching the surface.
- Precipitation in those areas in and surrounding the tropical Pacific (and remotely in the areas that ENSO affects) to evaluate the skill of precipitation predictions.
- Upper-level water vapor to evaluate the effect of seasonal to interannual variability, as opposed to greenhouse feedback of this quantity.

The overall recommendation, therefore, is to maintain global SST measurements and to maintain the TAO array.

Modeling Requirements

The National Research Council panel on the GOALS component of CLIVAR has made the following recommendations for developing improved models:

> Improvements are needed in all of the component models of the climate system in order to increase prediction skill in the seasonal to interannual time frame . . . . Atmospheric general circulation models need to be improved to a stage where, when driven with prescribed observed SST, they simulate realistically the observed annual cycle and interannual variability of the surface wind stress and heat flux, as well as the global atmospheric circulation and rainfall. . . . Similarly, oceanic general circulation models need to be improved to a stage where, with prescribed surface stresses and heat fluxes, they simulate realistically the observed annual cycle and interannual variability of SST, upwelling, upper-ocean heat content, convection, and subduction. The improvement of land surface process models (LSPMs) to a stage where they represent adequately the interaction between the land surface and vegetation and the atmosphere is necessary.[38]

The panel especially acknowledges the need for developing an integrated approach to modeling seasonal to interannual climate change and notes that:

> In addition to improving the individual component models of the climate system, the panel recommends an equally strong effort in coupling the component models together so that they better approximate the natural system. . . . Though somewhat simpler than GCMs, models of *intermediate complexity* should also be constructed. . . .
>
> With regard to applications and human dimensions, the panel recommends that *auxiliary models* be designed to predict societally important quantities not routinely produced by seasonal to interannual climate forecast models. . . . Auxiliary models include those used to make projections of agricultural yield, water availability, fish productivity, energy demand, economic impact, and so on. . . .
>
> Improved strategies should be developed for nesting high-resolution regional models and global climate models to infer detailed structures of regional climate anomalies forced by global boundary conditions predicted by coupled ocean-land-atmosphere models. Furthermore, the systematic and periodic intercomparison of models should be continued in order that the physical sciences and the user communities have available an ongoing assessment of the status of models. . . .

Global Monsoon Research Imperative

During the TOGA decade, a concerted effort was made to exploit the predictability that had been found in the coupled ocean-atmosphere system of the Pacific Ocean. Monitoring of the ocean and the atmosphere has provided data for diagnostic studies that have helped in understanding the processes that produce the El Niño and La Niña phenomena. Process studies have been conducted to explore physical associations that were difficult to understand but which were critical links in describing the totality of the phenomena. Numerical coupled ocean-atmosphere models have been constructed, with moderate success in forecasting seasonal to interannual variability in the tropical Pacific Ocean. However, for many years it has been apparent that there are predictable elements in other regions of the tropics as well. The existence of these elements may be seen in the relative success of empirical techniques in foreshadowing interannual variations in the summer rains of the Asian-Australian monsoon.

A major research imperative is to extend the successes of TOGA to the global domain. Of high priority is extension of the monitoring, modeling, and pilot studies of the Pacific Ocean to encompass the other major heat sources and sinks in other tropical oceans and tropical land masses. The principal aim would be to identify predictable elements in these regions and also to determine links with predictable ENSO elements, if they exist. Predictability of the extratropical circulations also should be sought. This goal will be accomplished by following predictable elements that have their roots in the tropics (e.g., ENSO) while at the same time seeking predictable elements that are inherent to the higher-latitude climate system. If inherent extratropical predictability does exist, it would probably come from climate memory associated with low-frequency ocean dynamics or hydrological processes over the land regions.

Observational Requirements

The U.S. GOALS program has devoted much effort to defining the observational requirements for global seasonal to interannual predictions. These requirements are summarized in Table 3.1, which is taken from *A Scientific Strategy for U.S. Participation in CLIVAR/GOALS.*[39] Note that variables are listed in priority order. Not surprisingly, there is considerable overlap between these variables and those identified as important in pursuing the other Research Imperatives identified in this report.

Land Surface Exchanges Research Imperative

Exchanges of water and energy at the land surface are major controls on the hydrological cycle. How evaporative and sensible fluxes interact with the atmo-

TABLE 3.1 State and External (or Forcing) Variables that Must Be Measured for the GOALS Program

Realm	State Variables	External Variables
Ocean	Upper-ocean temperature. Upper-ocean currents. Sea level. Upper-ocean salinity. Optical absorption. Sea ice extent, concentration, and thickness.	Wind stress. Net surface solar radiation. Downwelling long-wave radiation. Surface air temperature. Surface humidity. Precipitation.
Atmosphere	Wind structure. Thermal structure. Surface air temperature. Sea-level pressure. Water vapor structure. Columnar water vapor and liquid water content. Cloud cover and height.	Sea surface temperature. Net radiation at top of the atmosphere. Land surface variables (see below).
Land	Soil moisture. Snow cover and depth. Vegetation type, biomass, and vigor Water runoff. Ground temperature.	Precipitation. Net surface long-wave and short-wave radiation. Surface wind. Surface air temperature. Surface humidity. Evaporation. Evapotranspiration.

SOURCE: NRC (1998).

spheric boundary layer locally, compared to interactions in remote locations, largely determines the occurrence of low clouds, low-level convergence of wind patterns, and deep convection. These fluxes in turn depend heavily on precipitation and solar radiation from the atmosphere. Both the portioning of solar radiation and precipitation at the surface and the amount and ratio of evaporative and sensible fluxes depend on seasonally varying land cover properties related to vegetation. The land surface is highly heterogeneous with regard to these properties, so representing land surface only in terms of properties at the scale of atmospheric models is problematic and of questionable accuracy.

The processes responsible for evapotranspiration are now relatively well understood as a point measure. However, they depend in part on details of soil moisture distribution. These details are largely unmeasured and poorly understood at the scales of climate models. Two particular factors determining soil moisture levels are especially poorly understood with regard to representation in climate models: how to represent runoff removal from land surface, and what is and what determines maximum water-holding capacity of the land surface. Much of the continental surface outside the tropics has seasonal snow cover and, in some places, frozen soils, which modify the surface hydrological cycle and solar energy absorption. Snow acts as a water reservoir for months or more but can at times release copious amounts of water rapidly.

Greater understanding of land surface exchanges and their representation in seasonal to interannual prediction models will require a combination of process studies, model evaluation exercises, and model experiments. Much of the required activity can be undertaken effectively through the set of continental-scale experiments being fostered by the World Climate Research Programme. Among these experiments, the Global Energy Water-Cycle Experiment Continental-Scale International Project (GCIP) in the United States and the Large-Scale Biosphere Atmosphere Experiment in South America are of particular relevance to the seasonal to interannual component of the USGCRP. However, the knowledge and model improvement provided by these last two continental-scale experiments must be effectively merged with the results of ocean-atmosphere studies by the GOALS program, to create a coherent U.S. seasonal to interannual prediction program that focuses on the Americas.

Downscaling Imperative

GCMs are currently the primary tools for studies of climate variability and change. Because of computational considerations relating to nonlinear dynamic equations and the current capabilities of supercomputers, GCM global grids have horizontal resolutions on the order of 100 to 250 km. Unfortunately, information generated at that scale (uniformly applied over the grid) is inadequate to describe many small-scale features of importance to the hydrological and energy cycles. A good example concerning atmospheric aspects of the hydrological cycle is the role of clouds. Moist warm air is transported upward in narrow, cloud-scale regions (kilometers), inducing compensating subsidence of cooler air at large scales (hundreds of kilometers). An example related to land surface hydrology is the way that surface and subsurface runoff production is greatly influenced by the spatial and temporal heterogeneity of precipitation inputs, the heterogeneity of soil hydraulic characteristics and flow pathways, and the heterogeneity of antecedent conditions induced by downslope flows and controlled by topography.

While various LSPs have been developed (and are continuing to be developed) to model small- to large-scale interactions, further work is required on the methodologies to desegregate regional model outputs at the scales of hydrological processes. Both LSPs and hydrological models have many parameters that are tuned to the scale of the model. For example, a GCM LSP would use different parameter values than an LSP developed to work at catchment scale with local historical station data. Current GCMs simulate precipitation with reduced intensity and increased frequency.[40] Developing LSPs and hydrological models that will work with a variety of global and regional observational data would be useful for many studies. A stochastic precipitation disaggregation scheme has been developed that redistributes the GCM-calculated grid average precipitation into a subgrid scale to improve the modeled interaction of the atmosphere and land surface.[41] The authors demonstrate that this approach provides a more realistic partitioning of precipitation into snow and rain (judged on the basis of ground-based observations) and a spatial distribution that better conforms to the actual observed heterogeneity of rainfall patterns for the areas (of GCM grid size) that were tested. The latter point is particularly important, considering that, for instance, the total annual runoff volume generated in the Colorado River basin is due to precipitation falling over about 10 percent of the total surface area. The importance of the GCM-generated grid average precipitation relating to the region of actual interest is clear, with regard to water resource management issues at local and regional scales.

In addition to the above-mentioned downscaling concerns, complex modeling issues abound in runoff production. For example, the mechanism through which water is partitioned into runoff and infiltration when snow and ice melt is a critical unresolved issue. Most LSPs follow the lead of the prior generation of bucket models in assuming that runoff either instantly vanishes or in a few cases goes directly to the ocean. Flow-routing schemes are required to overcome this deficiency. The GCIP program is attempting to address some of these downscaling issues. Additionally, there is great need to understand the scale dependence of the inputs and outputs as well as how to adjust the scales to give the best possible predictions, so that our capability to interpret the effects of large-scale climate variability on regional and local scales can be improved.

Terrestrial Hydrology Research Imperative

Variations in climate at seasonal to interannual timescales have important implications for terrestrial hydrology. Although precipitation is the most important determinant of key terrestrial hydrological variables (streamflow, soil moisture, snowpack water content, and evapotranspiration), the land surface acts as a low-pass nonlinear filter, so that antecedent precipitation as well as current precipitation play important roles in smoothing the effects of climate variability at these timescales. The implications of land surface processing of precipitation at these timescales are not well understood. For instance, recent work in the Appalachicola-Chattahoochee-Flint (ACF) river system of the southeastern United States suggests that, even though a fairly strong ENSO signal can be detected in precipitation, the signal appears to be filtered out in the streamflow record, where it is much weaker. On the other hand, in the Columbia River basin, a strong ENSO signal is present in the streamflow record. Although it may be surmised that the links between winter precipitation (which is largely stored as snowpack) and spring-summer streamflow are likely to be more direct in the Columbia than in the ACF, the effects of land surface processing in seasonal to interannual signals in precipitation are still not fully understood. These effects are further complicated by temperature, which affects both rain-snow transition and evapotranspiration. For example, evapotranspiration mitigates the effects on streamflow of warm wet periods (especially in summer) and exacerbates the effects of cold wet conditions. Especially in the western United States, cold wet winters result in much larger snowpacks, and hence greater spring and summer runoff, than do warm wet winters.

For hydrological purposes, seasonal to interannual climate forecasts could have at least two important functions. The first is to forecast the evolution of hydrologically important surface variables (especially precipitation and temperature) using methods such as ensemble forecasting to represent the range of future conditions over the forecast period. There are mechanisms to extend current methods, such as extended streamflow prediction, to use ensemble forecasts of the time series of surface variables. Important research issues in developing this approach have to do with resolution of biases in the climate forecasts (especially for precipitation). Seasonal to interannual forecasts might also be used in a probabilistic (or risk) context. For instance, seasonal to interannual climatic variability might be reflected in changes in the 100-year flood in ENSO versus non-ENSO years. How best to achieve such forecasts remains to be determined, but the general strategy would be based on classification of the current condition and/or forecasts of the evolution of future conditions at the regional scale, combined with retrospective frequency analysis.

Observational Requirements: Land Surface Exchanges, Downscaling, and Terrestrial Hydrology Research Imperatives

The primarily hydrological observational datasets needed in support of the above imperatives can be described as follows.

Streamflow

The U.S. Geological Survey should take steps to ensure the long-term viability of the stream gages in the Hydro-Climatic Data Network, particularly those having at least 50 years of continuous record. Currently, most of these stations are funded cooperatively for a variety of operational purposes and are difficult to sustain for long-term research purposes.

Precipitation

Station Data

The United States must maintain existing long-term stations within the National Climatic Data Center (NCDC) cooperative network, particularly the subset of those stations that make up the Historical Climate Network.

Radar Precipitation Data

The National Center for Environmental Prediction has recently started to archive a merged WSR88-D (Doppler radar)/gauge product (4-km resolution) that covers most of the United States. The suitability of these data for climatological purposes needs to be evaluated, and steps must be taken to ensure the security of the long-term archive of these data and that they are freely available to the scientific community.

Surface Radiation

Only a very small number of stations now operate in the continental United States that collect a full suite of surface radiation observations (the SURFRAD network). The adequacy of this network for studies of seasonal to interannual variability should be evaluated.

Snow

Point Observations

Snow water equivalent point observations are collected primarily at Natural Resources Conservation Service Snow Telemetry sites in mountainous areas of the western United States. The suitability of these sites for long-term climate studies needs to be evaluated (the longest records from these stations date only to the mid-1980s). Snow depth measurements are collected at some NCDC cooperative stations. The feasibility of using some subset of these stations to measure snow water equivalent should be evaluated. The object is to achieve a much more uniform spatial distribution of station-based observations.

Areal Extent

NOAA's National Operational Hydrologic Remote Sensing Center and its National Environmental Satellite, Data, and Information Service (among other entities) produce satellite-based snow areal extent measurements of the continental United States and the world. These products are currently used for operational purposes but could prove extremely valuable for assessing such interactions as those between the continental extent of seasonal snow cover and large-area circulation patterns. Steps should be taken to ensure that these data are climatologically useful.

Algorithms

Satellite remote sensing algorithms to estimate snow water equivalent in a manner suitable for global studies (e.g., spatial resolutions of tens of kilometers) have been improved and may be suitable for seasonal to interannual timescale studies, notwithstanding problems remaining for forested areas. These products need to be assessed and archived at (or through) the National Snow and Ice Data Center.

Wind and Humidity

Although these wind and humidity data are collected at NCDC Surface Airways Stations, many of the records are affected by station and instrument changes, and their use for climatological purposes is problematic. Nonetheless, they are critical for computing potential evapotranspiration and provide reference values for approaches that can lead to spatial estimates (e.g., modeling combined with atmospheric profile data or analysis fields). Thus, more attention should be given to the climatological value of these observations.

Surface Air and Skin Temperature

Observations of surface air temperature are critically important to predict evapotranspiration and snow accumulation and melt. Surface air temperature measurements are routinely collected at NCDC cooperative observer stations as well as at National Weather Service manned observing stations. Because air temperature tends to have much higher spatial correlations locally than, for instance, precipitation, maintenance of an adequate station precipitation network should assure adequacy of surface air temperature measurements, provided that these variables are coincidentally collected. Direct observations of surface (skin) temperature are much more problematic. Surface observations have generally only been collected in research projects and are difficult to interpret. Nonetheless, skin temperature is a state variable predicted by most land surface schemes (some schemes predict an effective vegetation temperature as well). Thus, these measurements might be updated as well. Satellite sensors and algorithms can produce global estimates of skin temperature at time frequencies as high as daily; a ground network could play a critical role in validating and calibrating the long-term spatial records that are now being acquired.

Surface Energy Fluxes

Direct observations of surface energy fluxes (latent heat, sensible heat, and ground heat flux) have hitherto mainly been collected in conjunction with short-term research programs (e.g., the First ISLSCP Field Experiment and the Hydrological Atmospheric Pilot Experiments). However, recent advances in flux measuring instrumentation (see Chapter 2) indicate that their routine, long-term operation is now becoming feasible. A commitment has been made, for example, to continue long-term operation of some of the BOREAS tower flux sites. The instruments required for routine measurement of surface energy fluxes are a subset of those required to make the more difficult measurements of carbon dioxide for ecosystem research. However, in the case of seasonal to interannual studies, there is an additional need for near-real-time data provision. In the course of the next decade, a network of surface energy and carbon dioxide flux measurement sites should be established to characterize seasonal to interannual changes in the surface-atmosphere exchanges for major vegetation types in the United States and perhaps globally.

Soil Moisture

Soil moisture plays a key role in partitioning net radiation into latent, sensible, and ground heat fluxes, particularly in summer. Some studies have indicated the potential importance of feedbacks between soil moisture and climate, especially in the interior of the northern hemisphere continents in summer. Therefore, observation of soil moisture, through ground- or satellite-based observing systems, or both, is of great importance. A few networks in the continental United States collect ground-based point observations of soil moisture, including networks of the Illinois Water Survey and the Oklahoma Mesonet. While there are questions about how point observations of soil moisture can be interpreted in the context of small-scale spatial variability and about the lack of standard instruments, the feasibility of ground-based networks needs to be evaluated. With regard to remote sensing, both active and passive microwave sensors have shown potential in estimating near-surface soil moisture. Furthermore, in combination with modeling, these surface observations might be extended to greater depths. Many issues remain, and problems of soil moisture estimation from satellite sensors are themselves the subject of ongoing research. Nonetheless, passive microwave sensors have demonstrated the capability to map spatial and temporal soil moisture variability at the watershed scale. With a carefully designed sensor system and carefully formulated algorithms, such measurements can be made from space at the global scale.[42] Viable proposals for candidate satellite missions have been developed and should be given careful attention and support.

Vegetation

Knowledge of seasonal and interannual variability in vegetation properties is critical to understanding links between the land surface and climate at seasonal to interannual timescales. Satellite-based estimates of vegetation properties, such as leaf area index and greenness, are now fairly widely used in numerical weather prediction models. Earth Observing System-era developments (e.g., the moderate-resolution imaging spectrometer) will almost certainly improve the quality of these products. A long-term global archive of seasonal variations in vegetation properties must be preserved, along with sufficient metadata to resolve questions about any effects of changes in instruments.

NOTES

1. NRC (1996).
2. ENSO phases, in particular, Rasmusson and Carpenter (1983); northern hemisphere climate, Horel and Wallace (1981).
3. Cane et al. (1986).
4. NRC (1996). The report describes the TAO array and the other remote and in situ measurement systems providing continuously available data in the tropical Pacific, referred to elsewhere in this report as the ENSO Observing System.
5. Adapted from Mooley and Parthasarathy (1984).
6. Parthasarathy et al. (1988).
7. E.g., Trenberth (1997).
8. Blanford (1984).
9. Walker and Bliss (1932).
10. Hahn and Shukla (1976).
11. Shukla (1987).
12. E.g., Barnett et al. (1989), Vernekar et al. (1995).
13. Meehl (1987), Yasunari (1990), Yasunari and Seki (1992).
14. E.g., Khandekar (1991), Meehl (1994), Yang (1996).
15. Hastenrath (1990a, b).
16. Moura (1994).
17. Charney (1975), Charney et al. (1977).
18. E.g., Rind (1982), Mintz (1984), Delworth and Manabe (1989).
19. Koster and Suarez (1995).
20. Benjamin and Carlson (1986), Clark and Arritt (1995).
21. Modeling, McCorcle (1988), Paegle et al. (1996), Beljaars et al. (1996), Betts et al. (1996); observations, Mitchell et al. (1995).
22. Rasmusson (1967).
23. Betts et al. (1993).
24. Paegle et al. (1996).
25. Beljaars et al. (1996).
26. Seth and Giorgi (1998).

27. Cane et al. (1986).
28. Charney et al. (1950).
29. D. Chen et al. (1995, 1997).
30. E.g., Y.Q. Chen et al. (1995).
31. D. Chen et al. (1995, 1997).
32. Zhang et al. (1996).
33. A review is given by Lau (1997).
34. Betts et al. (1993).
35. As discussed by Avissar and Pielke (1989).
36. Busalacchi et al. (1981, 1983).
37. See NRC (1994) for a thorough discussion.
38. NRC (1998).
39. Ibid.
40. Gao et al. (1996).
41. Gao and Sorooshian (1994).
42. *Journal of Hydrology* (1996).

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4

Changes in the Climate System on Decade-to-Century Timescales

SUMMARY

Research on changes in the climate system on decade-to-century timescales has achieved notable successes in the past decade. The effective use of the paleoclimate record has revealed attributes of natural climate variability and has provided a context for the study of present and future global change. Findings about rapid climate change have been particularly enlightening, such as the recent recognition of decadal patterns in the atmosphere. This discovery is owed mostly to analyses of long-term, upper-air data, demonstrating the essential value of maintaining such long-term consistent records.

Recent advances in understanding climate prediction on timescales of decades to centuries include the following, among others: documentation and recognition of the scope of natural variability; documentation by calibrated satellite observations that clouds have a net global radiative cooling effect on the Earth-atmosphere system by about 15 to 20 W/m^2; achievements in understanding water vapor behavior and in feedback analysis, proposed and to some degree realized, on theoretical, observational, modeling, and methodological grounds; and understanding the role of volcanic eruptions as a climate-forcing factor, as seen in measurement and assessment of the impacts of recent eruptions.

This area of research has underscored the complexities and uncertainties of detecting and projecting climate change. It has become even clearer that determining the roles of anthropogenic forcing is inseparable from understanding the natural system. Anthropogenic global change cannot be assessed without adequate understanding and documentation of natural climate variability on timescales of years to centuries—in other words, without adequate baseline understanding. This understanding encompasses solar and volcanic variability; feedbacks

resulting from the interactions of water vapor, clouds, and radiation; and the massive heat fluxes associated with the motions of the air and oceans and the exchanges between them, among other phenomena, beyond quantified understanding of anthropogenic forcing itself. To evaluate anthropogenic forcing specifically, greater knowledge is also needed of tropospheric aerosols and the carbon cycle.

The primary characteristics of the climate system must be documented through consistent long-term observations. Finally, the subtlety of slow change over long timescales, in contrast to diurnal, seasonal, and interannual variations, can disguise its potential long-term severity and thus limit society's willingness to address potential problems in advance. The problem is much exacerbated, of course, by the uncertainty in our ability to forecast such change. All these considerations further underscore the importance of achieving better understanding of climate change patterns on decade to century timescales, including their rate and range of variability, likelihood and distribution of occurrence, and the sensitivity of climate to changes in forcing (natural and anthropogenic). With such improved understanding, we ultimately hope to forecast and detect change (distinguishing natural from anthropogenic), providing a foundation on which future policy decisions and infrastructure management can be rationally based.

A number of Research Imperatives must be met to understand climate change on decadal to centennial timescales:

- *Natural climate patterns.* Improve knowledge of decadal- to century-scale natural climate patterns, their distributions in time and space, optimal characterization, mechanistic controls, feedbacks, and sensitivities, including their interactions with, and responses to, anthropogenic climate change.
- *Paleorecord.* Extend the climate record back through data archeology and paleoclimate records for time series long enough to provide researchers with a better database to analyze decadal- to century-scale patterns. Specifically, achieve a better understanding of the nature and range of natural variability over these timescales.
- *Long-term observational system.* Ensure the existence of a long-term observing system for a more definitive observational foundation to evaluate decadal- to century-scale variability and change. Ensure that the system includes observations of key state variables as well as external forcings.
- *Climate system components.* Address those issues whose resolution will most efficiently and significantly advance our understanding of decadal- to century-scale climate variability for specific components of the climate system.
- *Anthropogenic perturbations.* Improve understanding of the long-term responses of the climate system to the anthropogenic addition of radiatively active constituents to the atmosphere and devise methods of detecting an-

thropogenic phenomena against the background of natural decadal- to century-scale climate variability.

INTRODUCTION

Climate research on decade to century ("dec-cen") timescales is relatively new. Only recently have we obtained sufficient high-resolution paleoclimate records, and acquired faster computers and improved models allowing long-term simulations, to examine past change on these timescales. This research has led to genuinely novel insights, most notably that the past assumption of a relatively stable climate state on dec-cen timescales since the last deglaciation is no longer a viable tenet. The paleorecords reveal considerable variability occurring over all timescales, while modeling and theoretical studies indicate modes of internal and coupled variability driving variations over dec-cen timescales as well.

Thus, dec-cen climate research is only at the beginning of its learning curve, with dramatic findings appearing at an impressive rate. In this area even the most fundamental scientific issues are evolving rapidly. Adaptability to new directions and opportunities is therefore imperative to advance understanding of climate variability and change on these timescales.

The paradigm developed to successfully study climate change on seasonal to interannual timescales cannot be applied to the study of dec-cen climate problems. That is, we have realized considerable success studying short timescale climate problems by generating hypotheses and models that are quickly diagnosed and improved based on analysis of the amply long historical records or quickly realized future records. For dec-cen problems the paleoclimate records are still too sparse and the historical records too short. Future records will require multiple decades before even a nominal comparison to model predictions is possible. Compounding the problem, the change in atmospheric composition as a consequence of anthropogenic emissions represents a forcing whose future trends can only be estimated with considerable uncertainty. As a result, progress requires considerable dependence on improved and faster models, an expanded paleoclimate database, and imposed (rather than calculated) anthropogenic emission scenarios. Heavy reliance on these methods and assumed forcing curves, without the benefit of real-time observations for constant model validation and improvement, implies a considerable effort for model validation through alternative means, improved understanding of the limits and implications of proxy indicators constituting the paleoclimate records, and detailed monitoring of emissions to help track actual rates. As for future observations, we can only now begin collecting the data to aid future generations of scientists in understanding dec-cen climate variability and change.

Climate variability and change on decade to century timescales involves all of the elements of the U.S. Global Change Research Program: natural and anthropogenic variability and change; past, present, and future observational networks and databases; modeling requirements; and physical, chemical, biological, and social sciences, with considerable attention to the human dimensions of climate change. The last focus is particularly important on dec-cen timescales because the magnitude of change is often, though not always, proportional to the timescale over which it varies. Consequently, climate change over these long timescales could produce much greater social, economic, and political impacts than shorter timescale variations, which are often addressed through disaster relief. On dec-cen timescales the impacts could be considerable, and adaptation and mitigation (of both the forcing and response) depend on policy decisions and investments in infrastructure. For example, the devastating floods that struck the Midwestern United States in 1993 and again in 1997 produced considerable hardship, loss, and destruction, requiring substantial recovery aid. However, if we knew that such floods occurred in, say, clusters of six or seven over a 20-year period, such information might dramatically reduce the negative impacts, through mitigation actions in policy and infrastructure. Perhaps we could even benefit in some ways from these events. Similar action would be possible, given advanced knowledge of the frequency or magnitude of extreme heat days for any particular region or, for that matter, knowledge of any other changes that might greatly affect agriculture, energy production and use, water resources and water quality, air quality, health, fisheries, forestry, insurance, recreation, and transportation. All of these areas are fundamental to society's well-being and would certainly be affected by any prolonged or abrupt shift in our climate system.

Unfortunately, the subtlety of slow change over long timescales, relative to diurnal, seasonal, and interannual variations, can disguise the potential severity of longer-term change and thus limit society's willingness to address the issues in advance. This difficulty underscores the importance of better understanding of decadal- to century-scale climate change, its rate and range of variability, its likelihood and distribution of occurrence, and its sensitivity to changes in forcing (natural and anthropogenic). With such understanding we may ultimately forecast and detect change (distinguishing natural from anthropogenic), providing a foundation for more rationally based policy decisions and infrastructure management.

CASE STUDIES

The four case studies presented below all relate to issues of dec-cen climate variability. The first case reviews findings from Greenland ice cores about the natural variability of the climate system. The second illuminates human responses to climate variability in Mesopotamia, as deduced from the paleorecord. A case of modern response to climate change is then described, concerning flood control on the American River near Sacramento. The fourth and final case study discusses emerging signals of the human-influenced climate system.

Natural Variability

The prediction and modeling of future climate change and its effects on the environment and people are two of the most challenging tasks facing science today. To understand possible future changes in climate, knowledge of past climate change is essential. As explained in Chapter 6, ice cores were recovered in 1992 after a five-year drilling effort in the Summit region of Greenland by the U.S. Greenland Ice Sheet Project Two (GISP2) and from the European project GRIP (Greenland Ice Core Project, sited 30 km to the east of the GISP2 site); and they have produced an unparalleled record of climatic change for the past 110,000 years.[a]

The cores revealed changes in the Earth's climate system over the past 150,000 years or so, with annual resolutions over the past several thousand years. One of the most remarkable findings from these cores was that the climate during the past several thousand years—the period we would consider modern climate—has undergone considerable natural variability, including large swings or cycles of climate and, even more remarkably, abrupt changes occurring in decades or less. In addition to these findings, the long record of climate change also suggests that, relative to earlier times in the Earth's climate history, these past several thousand years have shown relatively little variability in climate change. The implication is that the impressive, and often abrupt, swings in climate recorded over the past several thousand years may, if anything, understate the potential for natural climate variability.

The Summit region has proven to be an ideal site from which to recover deep ice cores. The approximate –31°C mean annual air temperature there and the minimal occurrence of melt layers throughout the record assure the in situ preservation of a broad range of gaseous, soluble, and insoluble measurements of the paleo-environment. Similarity of the GISP2 and GRIP records is compelling evidence that the stratigraphy of the ice is reliable and unaffected by extensive folding, intrusion, or hiatuses from the surface to 2,790 m (~110,000 years ago). This agreement between the two cores strongly supports the climatic origin of even minor features of the records and suggests that investigations of subtle environmental signals (e.g., rapid climate change events with one- to two-year onset and termination) can be rigorously pursued.

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[a] GISP2 successfully completed drilling through the base of the Greenland ice sheet and another 1.55m into bedrock in central Greenland on July 1, 1993, recovering the deepest ice core record in the northern hemisphere (3053.44m). GISP2, a component of Arctic System Science, is comprised of investigators from 22 institutions. Twenty programs with 46 types of measurements on the ice core comprise the deep drilling effort. Nine other programs provide direct information necessary for interpretation of the GISP2 ice core record.

A Distant Past: The Younger Dryas and Other Rapid Climate Change Events Over the Past 110,000 Years

The Younger Dryas was the most important rapid climate change event that occurred during the last deglaciation of the North Atlantic region. Previous ice core studies had focused on the abrupt termination of this event because this transition marks the end of the last major climate reorganization during the deglaciation. Most recently, the Younger Dryas has been redated, using precision, subannually resolved, multivariate measurements from the GISP2 core, as an event of 1,300 +/–70 years' duration that terminated abruptly at 11,640 years before the present (BP), as evidenced by a rise in temperature of about 7°C and a twofold increase in the snow accumulation rate. The transition into the Preboreal, the Preboral/Younger Dryas transition, and the Younger Dryas/Holocene transition were all remarkably fast, each occurring over a decade or less (see Chapter 6).

The isotopic temperature records show 23 interstadial (or Dansgaard/Oeschger) events, first recognized in the GRIP record and verified in the GISP2 record, between 110,000 and 15,000 years BP. These millennial-scale events represent quite large climate deviations—probably of many degrees in temperature, twofold changes in snow accumulation, order-of-magnitude changes in wind-blown dust and sea salt loading, and roughly 100 ppb (volume) swings in atmospheric methane concentration.

In view of all these measures, the events must have been regional to global in scale. They are seen in local climatic indicators, such as snow accumulation rate and isotopic composition of snow linked to temperature; in regional climatic indicators, such as wind-blown sea salt and continental dust; and in regional to global indicators, such as atmospheric concentrations of methane, nitrate, and ammonium. Some of the events are also readily identified in the ocean-sediment record in regions critical to global ocean circulation.

Since these cores were obtained, additional investigations, involving large numbers of proxy indicators of past climate change, from all of the different climate zones on Earth, have reinforced these initial findings and more clearly driven home the vulnerability of the Earth's climate system to natural variability. Consequently, these findings have changed our way of viewing the climate system and fundamentally undercut the notion that we live in a relatively stable climate system.

The Last 500+ Years: The Little Ice Age, Medieval Warm Period, and Fossil Fuel Era

The Little Ice Age and Medieval Warm Period environments are the most recent analogs for conditions cooler and warmer, respectively, than the present century. Each period can be characterized by interpreting the multiparameter

GISP2 series (e.g., CO_2, stable isotopes, major ions, accumulation rate, particles). GISP2 temperature modeled from oxygen isotopes reveals a relatively subdued temperature effect at this Greenland site for the Little Ice Age. More recently, year-to-year correlations between the GISP2 isotopic record and sea surface and land temperatures over the North Atlantic, covering the period 1840 to 1970, reveal changes in atmospheric circulation patterns, such as the seesaw pattern of the North Atlantic Oscillation, demonstrating the sensitivity of the isotopic record.

Levels of continental dusts and marine sea salts increased during the Little Ice Age in response to increased meridional circulation. The Little Ice Age is one of several glaciochemically identifiable climate events in the Holocene record that correlate with other paleoclimate records. The period is characterized by the most rapid onset of any Holocene cold period.

Measurements of CO_2 in air bubbles of the GISP2 core indicate that between 1530 and 1810 atmospheric CO_2 levels remained relatively constant at +/– 280 ppm(v). Thereafter, concentrations rose rather abruptly and smoothly connected to the atmospheric observations at Mauna Loa. Previously identified increases in sulfate and nitrate seen in south Greenland ice cores and attributed to anthropogenic activity were identified in the GISP2 core and contrasted to the preanthropogenic atmosphere. An observed increase in chloride at GISP2, as in the 1940s, is believed to be a byproduct of increased anthropogenic HNO_3 and H_2SO_4, since these compounds are believed to aid in the volatilization of HCl from sea salt aerosol.

Human Responses to Climate Change as Deduced from the Paleorecord

Although the issue of human response to climate change is controversial, several recent studies find close correlations in timing between climate change and changes in civilization. These studies have focused on changes in temperature in relation to high-latitude societies and changes in moisture availability for mid- to low-latitude societies. In regions on the ice margins, such events as the disappearance of the Norse colonies in Greenland during the mid- to late fourteenth century appear to be chronologically correlated at some sites with the occurrence of a few extremely cold winters and at others with the general amelioration of climate produced at the onset of the Little Ice Age.[1]

By utilizing climate-linked paleoclimate records, it was found that periods of decreased atmospheric circulation intensity in the North Atlantic, developed from the GISP2 ice core, could be correlated with discontinuous Dead Sea level records of drying,[2] which are a reasonable indicator for west Asian aridity.[3] The more detailed record reveals a close correlation between major periods of drying and major social disruptions in west Asian civilization.[4] Other research[5] has found that the driest period represented by a late Holocene lake sediment record from Mexico correlates closely with the collapse of the classic Mayan civilization around 750 to 900 AD.

A Modern Climate Change Dilemma: Flood Control on the American River

The significance of decadal- to centennial-scale climate variability is highlighted by a recent example of water resources planning.[6] Flood control projects are designed to protect facilities from a design flood or flow. The level of protection (i.e., the risk of project failure) provided against the design flood is assessed through statistical analysis of the historical flood record. The economics of a new flood control project are determined by comparing the expected monetary benefits of reducing flood risk and the associated project cost. Flood insurance programs rely on a similar analysis. The variability of flood risk at decadal to centennial timescales and its implications for flood control are discussed here in the context of the American River near Sacramento, California.

Flood protection for Sacramento is provided by the Folsom Dam together with a system of levees. The dam was designed in the late 1940s, based in part on a flood record extending back to 1905. Since the dam's design, there have been six floods (not including the 1997 flood) on the American River larger than all previously recorded floods (see Figure 4.1). The estimated frequency of exceedance of extreme floods has correspondingly increased. It now appears that a large part of Sacramento may not even have 100-year flood protection. Should new flood mitigation projects be based on an assessment of flood risk from the

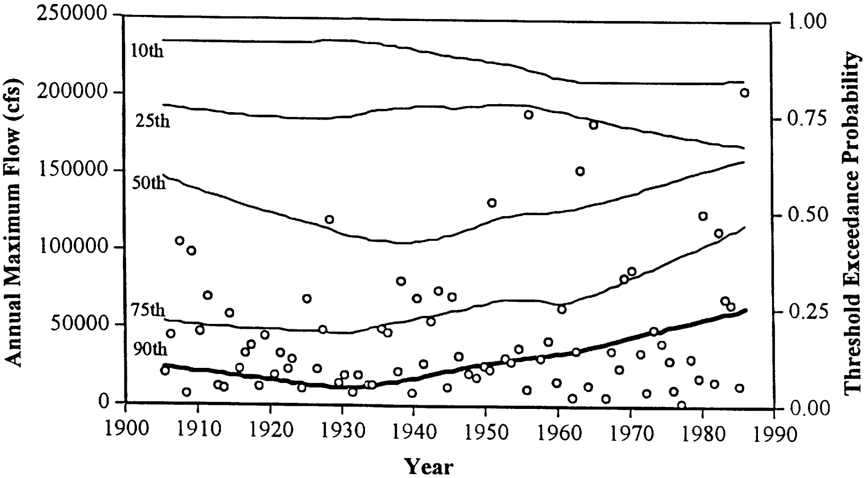

FIGURE 4.1 The time-varying probabilty of exceeding the 10th, 25th, 50th, 75th, and 90th quantiles of the full American River annual maximum flood record (shown as o), estimated by smoothing (with a 56-year span) a binary indicator (1 = exceedance, else 0) applied to the quantile. Note the trend reversal since about 1940, with an increase in the probability of exceedance of the rarer floods and a decrease for the more common floods. SOURCE: National Research Council (1995a).

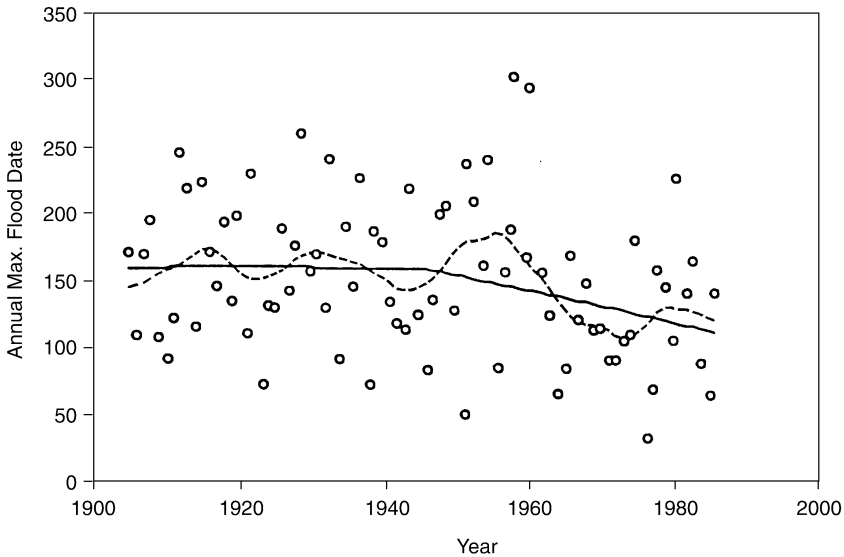

FIGURE 4.2 Date of annual maximum flood for the American River near Fair Oaks. Centennial and decadal trends are shown by the solid (56-year smooth) and the dotted lines (14-year smooth). SOURCE: National Research Council (1999).

entire flood record or from the past 50 years? A project designed to provide a 200-year level of protection based on the full flood record would provide less than 100-year protection based on the record since 1950. Project costs and potential flood damages could vary by over an order of magnitude depending on the protection level adopted. This decision-making dilemma was noted by the National Research Council Committee on Flood Control Alternatives in the American River Basin.[7]

Since about 1940, the annual maximum flow on the American River has also occurred earlier in the year (see Figure 4.2), with a decadal fluctuation superposed on this trend. This pattern has implications for the types of models (e.g., rain on snow dynamics instead of rainfall runoff) needed for flood forecasting and for real-time flood control. A number of factors, including improvements in streamflow measurement technology and urbanization of the watershed, may be responsible for these changes in the flood regime. However, structured decadal to centennial climate variations are a likely cause.

Others[8] argue that earlier snowmelt in California may be caused by a trend toward warmer winters there and a concurrent long-term fluctuation in winter atmospheric circulation over the North Pacific Ocean and North America. The fluctuation began to affect California in the 1940s, when the region of strongest low-frequency variation in winter circulations shifted to a part of the central

North Pacific Ocean that is strongly linked to California temperatures through the Pacific-North American (PNA) teleconnection pattern.[9] Since the late 1940s, winter wind fields have been displaced progressively southward over the central North Pacific and northward over the West Coast of North America. These shifts in atmospheric circulation are associated with concurrent shifts in both West Coast air temperatures and North Pacific sea surface temperatures and with earlier snowmelt and increased spring moisture fluxes in the American River basin.

Gridded ($5^o * 5^o$) monthly records of northern hemisphere sea level pressure (SLP)[10] and surface temperature[11] for the period 1899 to 1996 have been used to reconstruct space and time patterns of quasi-oscillatory large-scale climate patterns at quasi-biennial ENSO (El Niño-Southern Oscillation), decadal, interdecadal, and secular frequency bands.[12] For the analysis a 40-year moving window Multi-Taper Method/Singular Value Decomposition (MTM-SVD) was used. Simultaneous analyses of these datasets help identify dynamically consistent space- and time-coherent patterns of low-frequency climate evolution. Projections of the hemispheric low-frequency patterns of SLP and temperature at the grid point closest to the American River streamflow gauge are shown in Figure 4.3. The low-frequency SLP and temperature projections are obtained from the MTM-SVD analysis by summing over the reconstructions for the secular (>30

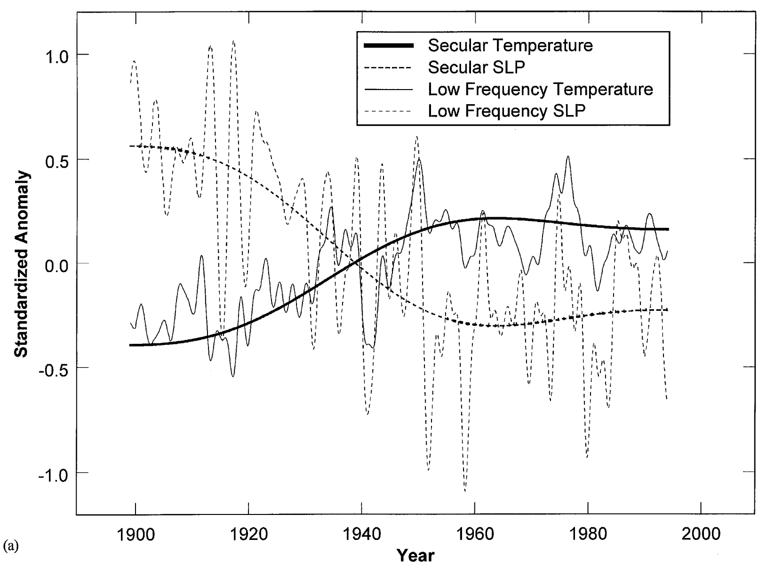

FIGURE 4.3 The secular and low-frequency components of SLP and temperature at the grid point nearest the American River from MTM-SVD. Note the secular trend toward warmer temperatures and lower pressure in the region, post-1940, coincident with the increased flood incidence and shift in flood timing. SOURCE: National Research Council (1999).

years), interdecadal (18-year period), decadal (10-year period), ENSO (3- to 6-year period), and quasi-biennial (2.2-year period) bands at the closest grid point. Note the secular trend for a shift to a lower SLP and warmer temperature at the American River region since about 1940. A remarkable connection between low-frequency climate and the high-frequency flood process is shown. Understanding and long-lead prediction of these fluctuations and their impact on regional hydrology and floods are key for dynamic flood risk assessment and better flood protection design and management. Flood insurance programs could be made much more efficient if long-term regional flood risk could be better assessed and "opposing" trends exploited.

Anthropogenic "Greenhouse" Warming

In 1896 Arrhenius pointed out that the increased concentration of CO_2 in the Earth's atmosphere, introduced by the burning of fossil fuels and compounded by other societal byproducts, could enhance the Earth's natural greenhouse warming, leading to an anthropogenic warming of the climate system and affecting civilization throughout the globe. A significant amount of research has been directed toward this problem, to understand if and how such an impact could be realized (or negated by natural feedbacks) and how to detect and interpret the source of such a warming. One of the most perplexing aspects of this research has been understanding the warming that the Earth has indeed experienced over this last century (see Figure 4.4) to determine whether this warming is natural, anthropogenic, or some combination of the two.

As noted in the Intergovernmental Panel on Climate Change (IPCC) Second Assessment (1996), the focus of recent climate change and variability research has shifted from the analysis of mean global temperature to that of temperature spatial distributions. This shift reflects the expectation that climate change may manifest itself irregularly in space and time. For example, it is clear that the relatively rapid global warming experienced over the past 20 to 25 years is distinguished by enhanced warming in winter (not evident in previous decades), with a strong warming over northern hemisphere land, but some small cooling over the northern hemisphere oceans.[13] This is the so-called COWL pattern: cold oceans and warm land pattern that is readily apparent in the global surface temperature data when comparing the past 20 years to the previous 20 years (see Plate 5).

The COWL pattern is a northern hemisphere winter phenomenon. A similar geographic pattern is simulated by numerous anthropogenic modeling studies and thus considered by some to represent one component of the so-called greenhouse fingerprint[14]—that is, a characteristic of the changing climate that might be uniquely associated with anthropogenic warming, as opposed to natural warming. Its presence in the actual observations has therefore been accepted as additional evidence of anthropogenic warming.[15]

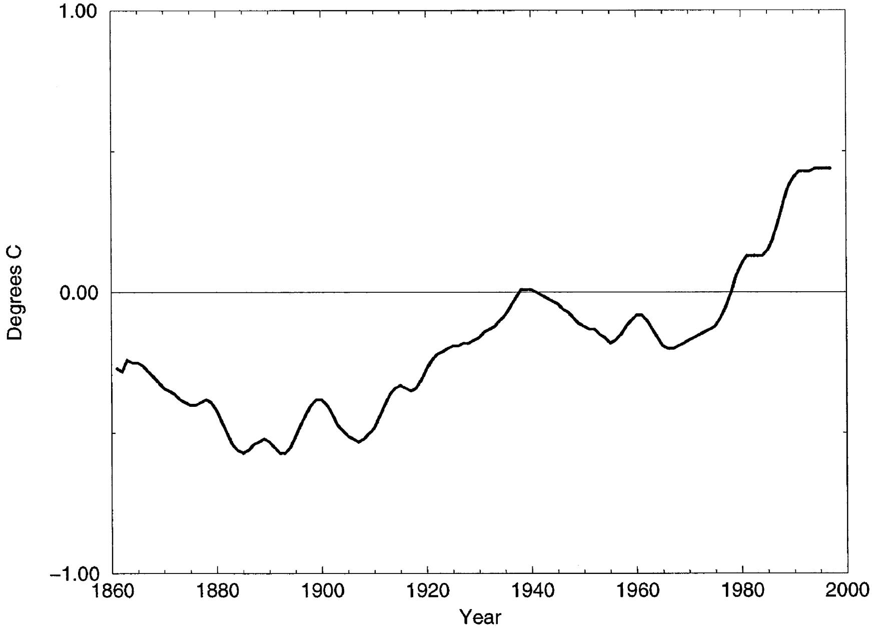

FIGURE 4.4 Annual global mean temperature for land areas from 1861 to 1997. The curve shows anomalies with respect to the mean temperature for the 30 years 1961–1990. SOURCE: Global Historical Climatology Network (GHCN); Peterson and Vose 1997. Courtesy of the National Climatic Data Center.

When the monthly averaged northern hemisphere surface temperature time series for this century is adjusted to eliminate the influence of the COWL pattern, two things become apparent:[16] a large fraction of the month-to-month variability, particularly apparent in the cool-season months, is no longer seen, and a significant fraction of the accelerated hemispheric warming observed since the mid-1970s, again concentrated in the cooling-season months, is also removed, making the summer and winter trends comparable (see Figure 4.5).

Further investigation suggests that much, though not all, of the accelerated warming since the mid-1970s that is attributed to the COWL pattern, and thus much of the COWL pattern itself during this period, can be explained by the similar time-averaged polarity of two natural patterns of climate variability— the North Atlantic Oscillation (NAO) and the PNA teleconnection (explained below; Hurrell, 1996). That is, over the past 20 years, the NAO and PNA patterns (the latter as indexed by another regional pattern, the North Pacific Index) both seem to show an apparently unusually persistent tendency, on average, to occupy states that favor a warming of Europe and Northern Asia by the NAO and a warming of North America by the PNA.

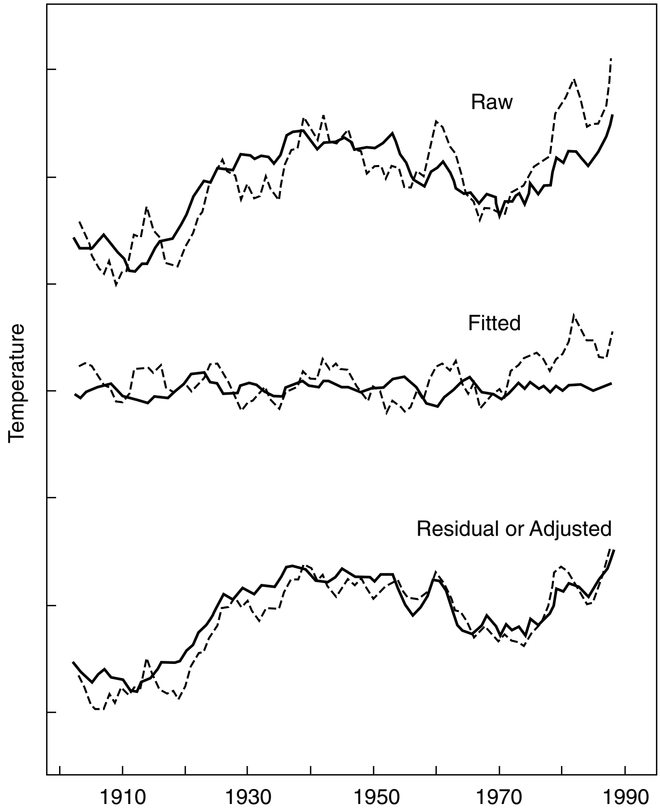

FIGURE 4.5 Smoothed monthly averaged surface temperature time series, northern hemisphere (top curves, dashed line is warm month's average, solid line is cool month's average; middle curves, same line indications but representing temperatures attributed to COWL pattern; bottom curves, same color indications but adjusted by eliminating COWL contribution shown in the middle set of curves. SOURCE: Wallace et al. (1995). Courtesy of the American Association for the Advancement of Science.

When this warming is removed, the global trends of the past two decades are similar, though still slightly larger, than the warming that occurred over several decades during the beginning of this century (e.g., from 1910 to 1940). Accordingly, several questions naturally follow: (1) Is this contribution of the NAO and PNA to the COWL warming a result of natural variability? That is, simply by chance will there likely be extended periods of time in which they display similar and relatively persistent polarity, or is this the manifestation of anthropogenic warming influencing the polarity of the natural climate modes? (2) Is the residual warming, that is, after removal of the COWL contribution, natural variability or anthropogenic warming? (3) What are the relationships among the COWL pattern, greenhouse fingerprint, and natural climate patterns? Such issues must be addressed to advance our understanding of climate variability and change over decadal to century timescales and to evaluate natural and anthropogenic influences. These and other equally important issues are articulated further in this chapter.

A RESEARCH AGENDA FOR THE NEXT DECADE

This section examines Research Imperatives and associated Scientific Questions that should guide future research on climate variability and change on decadal to century timescales.

Issues Regarding Climate Variability

By their very meanings, climate change and climate variability implicitly refer to reference, normal, or climatological mean states. Because climate varies on all timescales,[17] one mean can serve as a reference state for the study of variability on shorter timescales while itself changing on longer timescales. In practice, whatever the definition used for the mean, an anomaly is the difference between some observed state of the climate system and that mean. Climate change and variability are characterized in terms of these anomalies. Fortunately, as the study of such anomalies develops, it becomes increasingly apparent that they are not randomly distributed in space and time but often appear to be organized in relatively coherent spatial structures that tend to preserve their shape while varying their amplitude and sometimes their phasing through time. Though the precise nature and form of these structures, or patterns, vary to some extent according to the statistical methodology used in the analysis, a rather consistent set of regional characteristics is generally found to be associated with the variant patterns. In short, in studying climate variability and change, the study of patterns is a natural development.

To date, we do not have a comprehensive inventory of global patterns, nor do we understand their mechanisms, couplings, longevity, or full implications for climate prediction. However, study of the most thoroughly investigated pattern, ENSO, which dominates the tropical Pacific, led to the first-ever successful climate predictions while yielding considerable insights about the climate system, the nature of its couplings, scales of influence, and other fundamental findings. Many other patterns, while not as well documented or studied, appear to be related to regional climate, others to the frequency of hurricanes, the nature of the ocean's thermohaline circulation, agricultural yields, and regional fish inventories, among other things. These patterns vary over a broad range of space and timescales; their relative phasing can dominate global temperature variations; and they often show regional and global teleconnections, covary with other climatological variables, and seem to focus different forcings and processes into single coherent responses. Because of these attributes and covarying relationships, further study of patterns may ultimately yield benefits like those obtained through the study of ENSO. Patterns thus provide one obvious avenue to pursue the search for predictive climate signals—that is, a manageable set of components into which a complex climate system can be decomposed.

Patterns in the Climate System

The literature is replete with descriptions of patterns covering a broad range of climatological variables and spatial scales. Several of these patterns have received considerable attention in recent years, and their names are now firmly established in the climatological lexicon. One goal of this chapter is to briefly describe the more widely referenced patterns that vary on decadal or longer timescales. This review thus serves as an abbreviated glossary for the remainder of the text while covering a representative selection of patterns, their characteristics, couplings, and relationships. The review also presents issues in interpreting the roles of patterns in climate variability and change over decadal to century timescales.

The North Atlantic Oscillation

The NAO is a predominantly wintertime, regional, sea level pressure (SLP) pattern whose influence extends across much of the North Atlantic and well into Europe (see Figure 4.6). A considerable part of its variance resides in a decadal-scale band.[18] The NAO is often indexed by the difference in SLP in Iceland (representing the strength of the Icelandic, or Newfoundland, low) and the Azores or Lisbon (near the central ridge of the Bermuda and Azorean High). Correlation of the NAO index to surface air temperature and sea surface temperature (SST) further reveals the degree to which the pattern is shared by the North Atlantic, the northern part of Europe, and northern Asia.[19] Typically, when the index is high, the Icelandic low is strong, which results in the increased influence of cold Arctic air masses on the northeastern seaboard of North America and enhanced westerlies introducing warmer, moister air masses to western Europe in winter.[20] Thus, NAO anomalies are related to wintertime temperature and precipitation downstream over Europe and across Russia and Siberia.[21] They have also been linked[22] to changes in the thermohaline circulation in the North Atlantic,[23] the cod stock in the northwest Atlantic,[24] and the mass balance of European glaciers.[25]

The Pacific-North American Teleconnection

The PNA is a large-scale teleconnection between the North Pacific Ocean and North America that appears as four distinct cells in the 500 mb geopotential height field. An index of this teleconnection pattern was created[26] through a

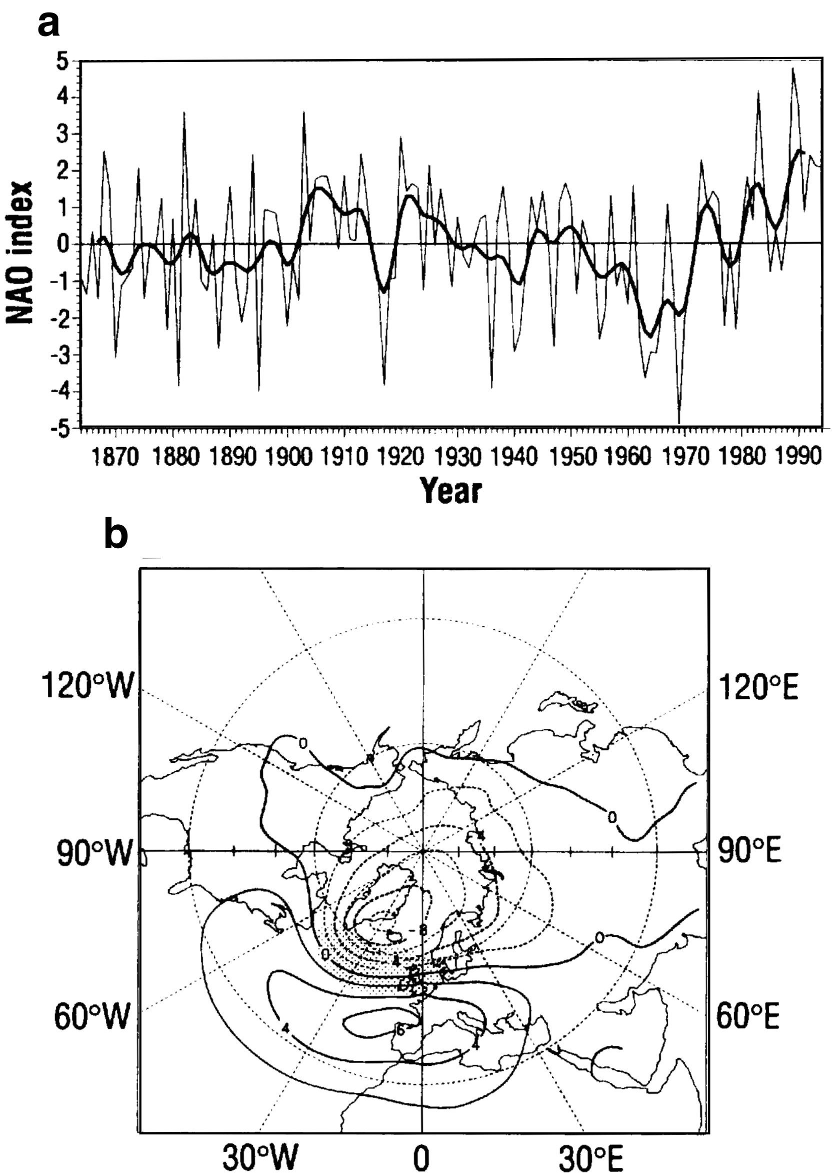

FIGURE 4.6 (a) Variations in the NAO index since 1864. (b) Difference in sea level pressure between high and low NAO index years, showing region of NAO influence. SOURCE: Hurrell (1995). Courtesy of the American Association for the Advancement of Science.

weighted average of 500-mb normalized height anomaly differences between the centers of the four cells; that is, the height anomaly differences between the North Pacific and Hawaii and between Alberta, Canada, and the southeastern United States (see Figure 4.7). However, the PNA also appears in SLP[27] as well and can be depicted by the North Pacific Index.[28] The North Pacific Index is expressed as the areally averaged SLP over a large area of the North Pacific Ocean near the center of the Aleutian low.

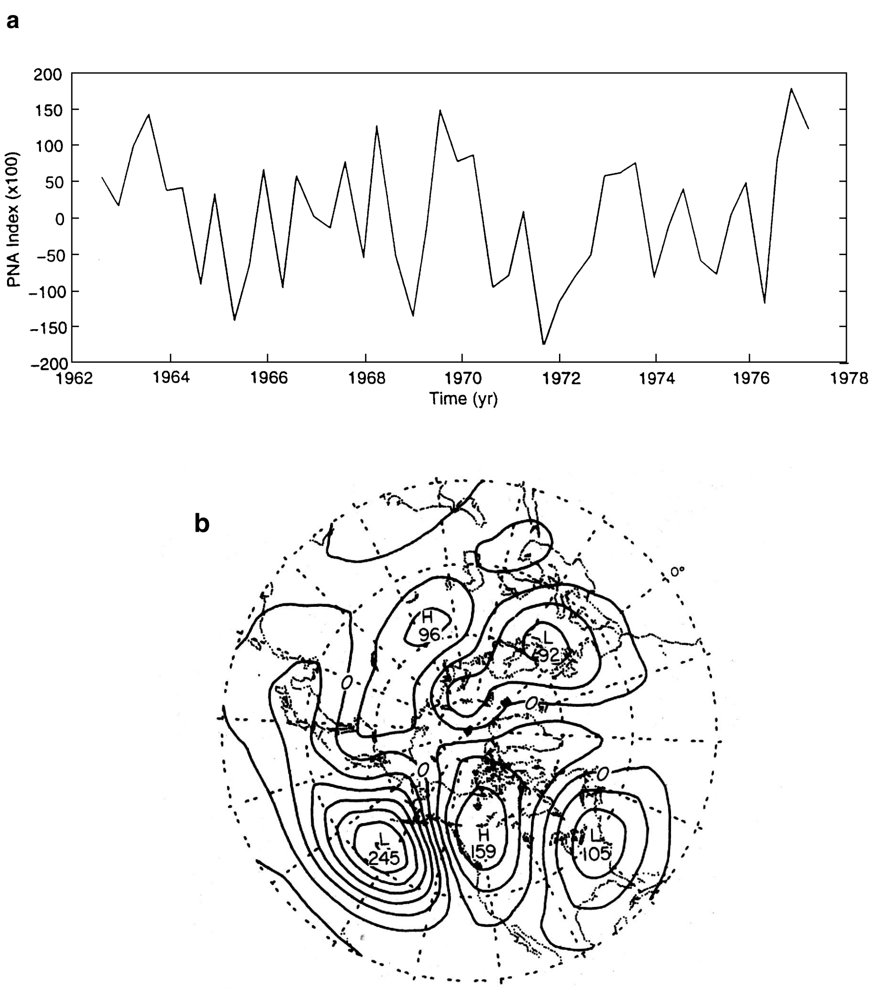

FIGURE 4.7 (a) Variation in the Pacific-North American (PNA) teleconnection index since 1962. (b) Region of PNA influence. SOURCE: Wallace and Gutzler (1981). Courtesy of the American Meteorological Society.

PREDICTION OF NE BRAZIL RAINFALL

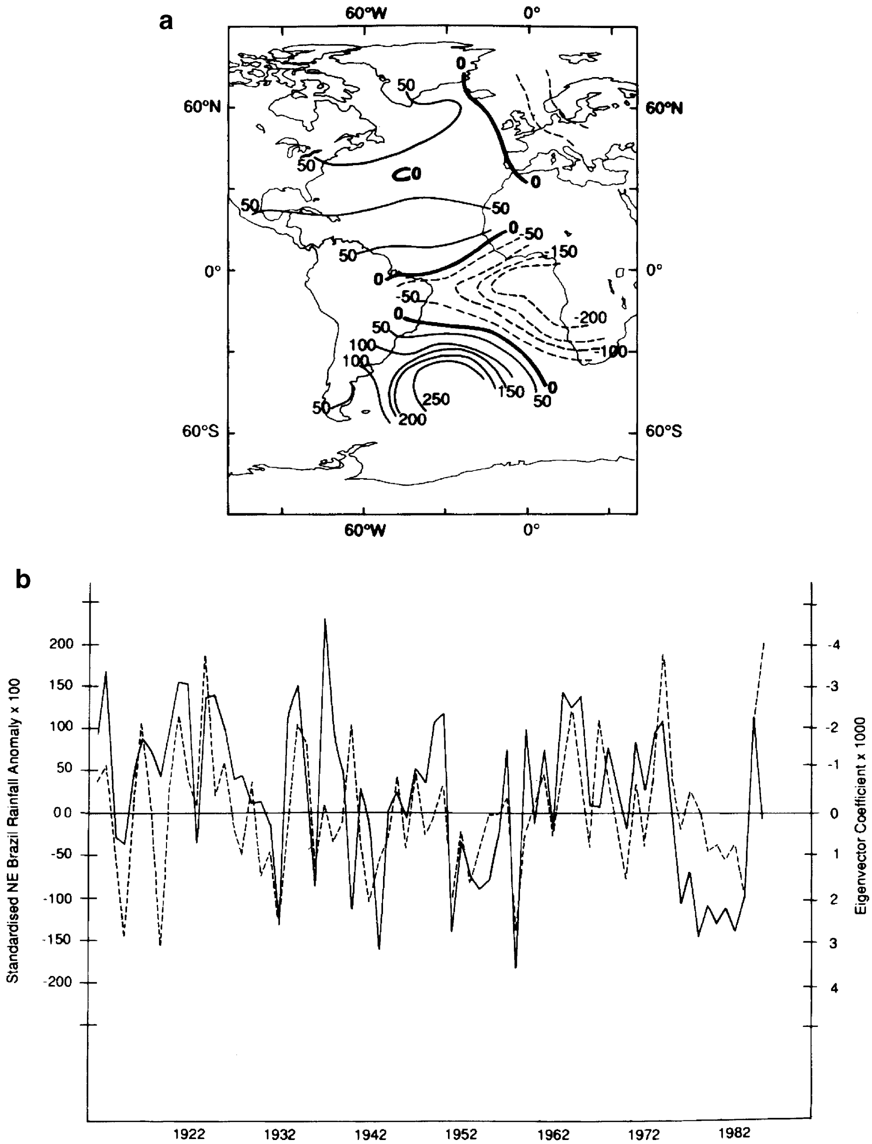

FIGURE 4.8 (a) The spatial EOF pattern of the Atlantic SST that is most associated with rainfall in Nordester, Brazil. (b) Time series (solid line) of the March-May values shown in (a) and north Nordeste Brazil rainfall anomalies (dashed line). SOURCE: Ward and Folland (1991). Courtesy of John Wiley & Sons Ltd.

The Pacific-North America pattern is highly correlated with ENSO,[29] and the North Pacific Index is highly correlated with the Southern Oscillation,[30] suggesting a broader extratropical influence of ENSO, though the low-frequency variability of the Pacific-North America pattern and the North Pacific Index may influence the ENSO phenomenon as well, as discussed below.[31] Decadal variability in the Pacific-North America pattern is also thought to be responsible for a significant amount of the variance in the salmon inventory along the northwest Pacific coast.[32]

The West Pacific Oscillation, North Pacific Oscillation, and Pacific Decadal Oscillation are smaller North Pacific patterns characterized by the areally averaged SLP in the western, central, and eastern North Pacific,[33] respectively. Both the West Pacific Oscillation and the North Pacific Index show a strong correlation to ENSO, although they are only weakly correlated to each other.

Tropical Atlantic SST

The tropical Atlantic Ocean shows a coherent structure in SST. There, the dominant empirical orthogonal function pattern of SST often shows a warm pool in the tropical North Atlantic and a complementary cool pool in the tropical South Atlantic, or vice versa. These contrasting pools seem to vary coherently over decadal timescales, though they vary independently on shorter timescales in their regions. Consequently, the general pattern is sometimes referred to as the Atlantic Tropical Dipole, though the lack of a clear consensus on the actual dipole nature of the pattern leaves many referring to it simply as the Tropical Atlantic SST variability. This low-frequency SST phenomenon is associated with anomalies in rainfall over Brazil and northern Africa (see Figure 4.8). It has been suggested[34] that the decadal changes in the SST in the subtropical North Atlantic may also be responsible for changes in the distribution and intensity of hurricanes in this region.

Decadal ENSO-like Pattern

The low-frequency covarying changes in the tropical Pacific atmosphere and ocean strongly resemble the pattern of the interannual ENSO phenomenon, including teleconnected anomalies in the midlatitude atmosphere and ocean of the North Pacific region (see Figures 4.9 a and b). The decadal ENSO-like anomalies are also teleconnected throughout the tropics, with large concurrent changes in tropical Atlantic and Indian Ocean SST,[35] as well as in the North Pacific Ocean and overlying atmosphere.[36]

The past few decades have experienced a warm phase of this climate anomaly, which has preceded a significant reduction in the alpine glaciers throughout the tropics.[37] In addition, the frequency of precipitation, streamflow, and snowpack in

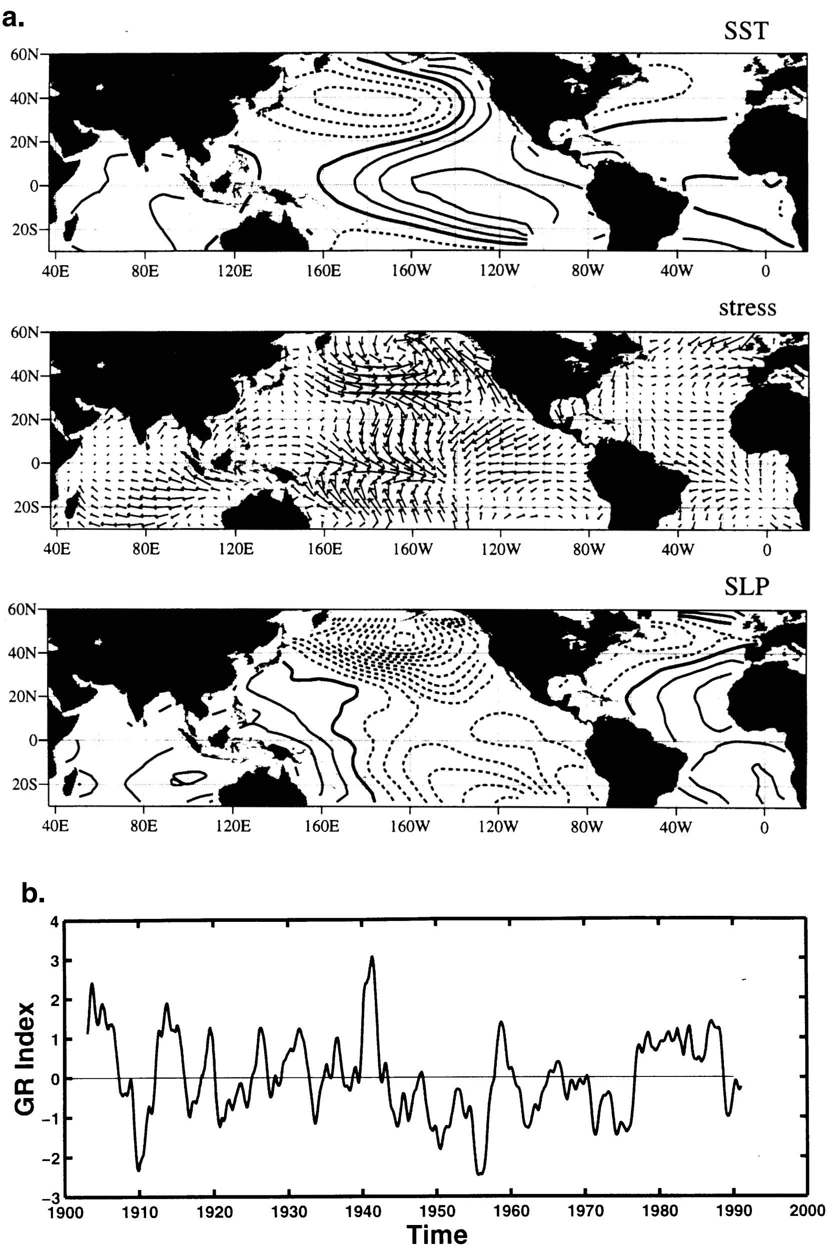

FIGURE 4.9 (a) Global residual SST pattern from which the linearly related ENSO variability has been removed. (b) Time series of the pattern displayed in (a), which indicates that the ENSO-like pattern primarily shows decadal- to century-scale variability. SOURCE: Zhang et al. (1997). Courtesy of the American Meteorological Society.

northwestern and southwestern North America[38] are well correlated with this time series of the decadal ENSO-like climate phenomenon.

Other Patterns

The patterns described above, while prominent in the literature and displaying variability on decadal timescales, represent only a subset of the decadal- to century-scale patterns identified and may or may not be of any more value than patterns not discussed here. For example, a number of regional atmospheric patterns have been analyzed, such as the North Pacific Oscillation,[39] West Pacific Oscillation,[40] West Atlantic Pattern,[41] and Pacific Decadal Oscillation.[42] A completely different kind of pattern, involving sea ice, has been found in the Southern Ocean. The Antarctic Circumpolar Wave is characterized by deviations in the Antarctic sea ice extent from monthly climatological averages, although it is also apparent in surface wind, SST, and SLP anomalies along the Antarctic polar front, near the winter marginal ice zone.[43] It is also highly coherent with temporal variations in ENSO[44] and Indian Ocean monsoons.[45] Other atmospheric patterns have been identified in the Southern Hemisphere,[46] though the data are frequently too few to allow detailed analyses.

In addition, there are structures that might be considered climate patterns, although they are often related to the other patterns or presented in a similar manner. For example, the Asian monsoon, while predominantly a seasonal signal, is strongly correlated with ENSO and shows decadal variability as indexed by precipitation and wind speeds over India.[47] Some investigators treat this monsoon pattern as a distinct, decadally varying pattern. Also, global thermohaline circulation has been tied to distinct changes in the ocean surface conditions and NAO in the North Atlantic Ocean. Extensive studies have shown the relationship between the NAO, ocean conditions, and thermohaline circulation, although no unique pattern has been defined.

Finally, the COWL pattern, while not a fundamental mode of climate variability, as defined by the decomposition of climatological variable fields, or a particular climate phenomenon, does appear to represent a distinct geographic distribution of near-surface temperature anomalies. Despite the apparent short-term memory of the COWL pattern, it displays long-term variability, as discussed in the case study above of anthropogenic “greenhouse” warming. Thus, COWL does represent another pattern and is often cited as such.

Research Imperatives for Explaining Climate Patterns

The large heat capacity and slow changes of the ocean must play a considerable role in climate anomalies persisting or evolving over decade to century timescales. This role is directly realized through SST, which sets the thermal contrast between the atmosphere and ocean and thus controls (together with shear) the heat flux. Since the heat capacity of the ocean is so much greater than that of the atmosphere, a minuscule change in ocean surface temperature corresponds to a substantial change in the overlying atmospheric column temperature. Thus, SST exerts a considerable influence on the atmospheric surface layer temperature and pressure. The decadal variability of the patterns, their covariance with SST and sea surface salinity (SSS), and their obvious geographic distributions reflecting the underlying distribution of ocean and land masses suggest that these variations and their changes on dec-cen timescales must be addressed as a coupled ocean-atmosphere problem (consistent with our current treatment of the ENSO phenomenon).

Therefore, the coupled air-sea system warrants special attention when considering longer-timescale variability of climate phenomena. In particular, several existing hypotheses predict the nature of the air-sea interaction responsible for tropical-extratropical climate links (e.g., the relationship between ENSO and PNA, or between TAO [Tropical Atmospheric-Ocean] and NAO).These hypotheses typically posit the fast propagation of an anomaly from the tropical regions (by standard atmospheric processes, or Kelvin or Rossby wave instabilities in the ocean, or western boundary current propagation) to the extratropics, followed by a slow return to the tropics via the ocean circulation system (e.g., subduction,[48] gyre circulation,[49] and thermocline subductive processes[50]), as discussed above. Because it will take so many years to test for these mechanisms through observational networks, a fundamental issue at this stage is to evaluate more fully the likelihood and signature of these different mechanisms to better focus future observing networks toward identifying the operative mechanisms.

Additionally, the coupled modes of climate variability must be clearly defined. That is, we need to define those physical modes of operation in the coupling of sea and air processes, that is, modes that would not exist without the presence of both media. Along these lines, we must determine whether all of the climate patterns fall into this classification or whether the patterns simple reflect the Hasselman[51] theory of climate change, in which the patterns and coupled modes of variability are simply the result of a white noise (weather) forcing over an alternating distribution of high-heat capacity ocean and low-heat capacity land surfaces (this can be considered the null hypothesis).

The relationship and linkages among the climate patterns, thought to reflect coupled air-sea interactions, also must be further clarified. For example, the decadal variability of ENSO and its relationship to the PNA and other North Pacific climate patterns has been noted, and ENSO's wintertime 500 mb height anomaly pattern of decadal variability is very similar to its interannual variability.[52] In the other fields (SST, SLP, and wind stress) the leading empirical orthogonal function pattern of decadal and longer timescale variability looks very similar in shape to ENSO (with a slight extension into the extratropical North Pacific). Despite a number of hypotheses suggesting the reason for this pattern shape, and some knowledge of the mechanism explaining the longer-scale variation in ENSO, there is no clear understanding of how ENSO and other climate phenomena interact with and regulate each other, invoking processes operative on different timescales yet producing spatial distributions that are quite similar regardless of timescale. These phenomena need further attention and clarification.

While there are a number of coupled modes, or observed patterns of covariation, between atmospheric fields (e.g., wind stress, SLP) and ocean surface and subsurface property fields (e.g., SSS, SST, thermocline salinity and temperature, and water mass migrations), the causal and controlling mechanisms of these patterns are not known at this time. Because these relationships will provide direct insights into the mechanisms that communicate climate anomalies between the ocean and atmosphere, and thus preserve and propagate the anomalies in both space and time, it is imperative that we gain improved understanding of these covarying relationships.

Better description and understanding are also needed of the relationships between pattern components (e.g., SST) and regional climate anomalies (e.g., rainfall), as seen in the case of the tropical Atlantic SST and African and Brazilian rainfall. The fundamental mechanisms of these relationships also must be determined. Such relationships are among the more critical patterns to investigate, since understanding them may allow prediction of seasonal influences.

Finally, while the implications of a change in the thermohaline circulation for climate are still unclear, there seems to be a coupling between the thermohaline circulation of the North Atlantic and the thermohaline circulation in that region, as indicated by the Great Salinity Anomaly of the 1960s.[54] An improved documentation of this relationship and analysis of its mechanisms and implications are required to help define the relationship and its significance.

To understand all such patterns in the climate system, the community is challenged by the following three interdependent research imperatives:

1. *Natural climate patterns.* Improve knowledge of decadal- to century-scale natural climate patterns, their distributions in time and space, their optimal characterizations, mechanistic controls, feedbacks, and sensitivities, including their interactions with, and responses to, anthropogenic climate change.

   Meeting this goal—and the related objectives discussed in the section on climate components below—requires long-term calibrated observations. This need therefore entails two major supporting research imperatives:
2. *Paleorecord.* Extend the climate record back through data archeology and paleoclimate records for time series long enough to provide researchers with a better database to analyze decadal- to century-scale patterns. Specifically, achieve a better understanding of the nature and range of natural variability over these timescales.
3. *Long-term observational system.* Ensure the existence of a long-term

observing system for a more definitive observational foundation to evaluate decade-to-century-scale variability and change. Ensure that the system includes observations of key state variables as well as external forcings.

Key Scientific Questions

To address the Research Imperatives above, some difficult Scientific Questions must be answered. Despite the uncertain roles of patterns and coupled modes in global warming and climate change more generally (including those changes important for climate prediction), it is clear that these patterns and coupled modes occupy large spatial areas, describe significant climate variance, and bridge high-, mid-, and low-latitude zones, thus representing potential means through which coherent climate variations and change may be propagated globally. As noted earlier, patterns emerge naturally in the study of climate anomalies and change; moreover, their study is consistent with the IPCC Second Assessment (1996). Identification of coherent patterns with coupled modes that explain significant spatial and temporal variability offers hope that a signal may be found in what otherwise appears as conspicuous noise. The apparent persistence of such patterns, even allowing for their possible slow evolution, provides additional hope that this signal may be exploited to predict and address future change and variability. Moreover, the relationships observed between specific climate pattern dispositions and regional climate characteristics supports the notion that better understanding of these relationships may allow short-term seasonal predictions for some regions.

To realize these potentials, considerable effort must also be invested in improving our general understanding of patterns and coupled modes, their mechanisms (dynamic and thermodynamic, natural and anthropogenic), couplings, feedbacks, and sensitivities. These are truly cross-disciplinary issues, requiring a strong interdisciplinary approach. Specifically, we must address the following Scientific Questions:

- *What is the longevity of patterns and their spatial/temporal variance?* Observed climate patterns offer tantalizing evidence that some part of the Earth's climate shows spatially and temporally coherent structure, with some degree of (predictable) persistence in a time-averaged sense. However, the fundamental patterns themselves may be transitory phenomena, reflecting the current configuration of a slowly changing climate. In fact, it has been suggested that, prior to the start of the twentieth century, the NAO displayed a different influence on European climate, in which case its general characteristics may have been different than today.[54]
- *What is the best way of characterizing the known patterns and are there additional patterns of interest?* Specifically, what are the salient features of

the patterns, covarying components, coupled modes (including regional influences and correlations with the climate attributes of Chapter 6), sensitivities to analytical techniques, spatial distribution, and teleconnections? Likewise, robust optimal indices of these patterns should be established. Some of the indices now used, while convenient, do not capture much of the spatial and temporal complexity of the coherent atmospheric circulation patterns they represent. For example, the Bermuda-Azorean High remains relatively stable in its spatial orientation, but the Icelandic low often migrates southward to Newfoundland. Thus, the North Atlantic SST pattern tends to show a rotation around the basin[55] that a simple dipole index between two fixed points, such as the NAO, cannot capture. Therefore, while the indices have proven sufficient in their ability to simplify the temporal history of complex patterns and demonstrate the patterns' broad spatial coherence and importance, additional research is required to better characterize the patterns and isolate their significant characteristics. That is, more robust indices must be developed. Additionally, what patterns and coupled modes exist in currently data-poor regions and what are their spatial and temporal characteristics?

- *Which patterns represent true dynamic modes and which are simply statistically consistent structures or geographically forced distributions?* Are identified patterns fundamental modes of climate variability reflecting coupled internal and external dynamics and thermodynamics? Or are they simple reflections of the land-sea distribution in keeping with the Hasselmann (1976) theory of climate change? Or are they the consequence of simple statistics or chaos, representing attractors or random but spatially consistent distributions? This understanding is fundamental to assess their value in long-term forecasting and prediction of climate change and variability.
- *What mechanisms generate, maintain, and modify the patterns? What is the role of those mechanisms in the spatial propagation of regionally initiated variability and change? What are their critical dependencies?* Certain mechanisms control the spatial and temporal evolution of the patterns and their broader influences or teleconnections. It is necessary to understand how a change in the state of a pattern in one location may dictate the regional climate in some more remote location. Such understanding will also reveal how a local disturbance may influence the dominant regional pattern, leading to the broader propagation of the anomaly, thus revealing controlling components of the climate system.
- *What is the relationship between the observed climate patterns and global warming?* Is the contribution of the NAO and the PNA patterns to the COWL warming a result of natural variability? That is, by chance will there be extended periods of time in which they display similar and relatively persistent polarity or is this the manifestation of anthropogenic

warming through the polarity of the natural climate modes?[56] That is, is the residual warming after removal of the COWL contribution attributable to natural variability or anthropogenic warming? What are the relationships between the COWL pattern, the greenhouse fingerprint, and natural climate patterns? In other words, how do the natural modes of the climate system respond to different changes in forcing, natural or anthropogenic? Are there unique characteristics or response modes? What controls the degree and nature of the spatial coalescence? How do they covary?

Components of the Climate System

While the existence of climate patterns offers hope that some part of climate variability may be related to these patterns' states, ultimately we must understand the physics controlling the evolution of the climate system in general as well as the patterns themselves. For example, understanding relationships between climate patterns and specific climate attributes may afford us statistical forecasting capabilities, but they will be limited to configurations or changes that have already been documented. Any attempt to forecast future variations or change, particularly in response to alterations in external or internal forcings, requires that we comprehend the underlying physical and biogeochemical interactions that control the responses and various feedbacks of the broader climate system of which the patterns are only the more convenient manifestations.

This section therefore looks at the component, or discipline-specific, issues that must be resolved to most efficiently advance our understanding of climate variability and change on decade to century timescales.

The atmosphere is a critical climate system component through which climate change and variability are registered. However, on dec-cen timescales, variability and change in the atmosphere, with its intrinsically short timescales, must involve considerable contributions in the form of couplings and feedbacks from the complex boundaries—the oceans, land, cryosphere, and biosphere. Thus, for convenience the climate system can be divided into four distinct components—the atmospheric circulation and three atmospheric boundary components, the oceans, cryosphere, and land and vegetation. There are also two coupled components to consider: the hydrological cycle (including the rates, paths, and storage of water through the atmosphere and at boundaries), and the chemical composition and radiative balance of the atmosphere (which includes the atmosphere and boundary coupling as well, in addition to representing the fundamental forcing of the system). The first four categories, then, are the fundamental components of the climate system (which themselves involve some dependence on their boundaries), followed by two coupled components that intimately involve the atmosphere and its boundaries. The last two are similarly critical areas of study in understanding the forcing of change and variability in the atmosphere, and they are of particular relevance to understanding anthropogenic change.

Research Imperatives for Characterizing Climate System Components and Perturbations

To characterize the climate system sufficiently, we need to take it apart, understand how its pieces work, and then "reassemble" the system. We also need to understand how the system responds to perturbations. Two Research Imperatives can guide this process. After presenting these imperatives, we turn to specific issues and key Scientific Questions for each major type of climate system component.

- *Climate system components:* Address those issues in terms of individual climate components whose resolution will most efficiently and significantly advance our understanding of dec-cen climate variability.
- *Anthropogenic perturbations:* Improve understanding of the climate system's long-term response to anthropogenic additions of radiatively active constituents to the atmosphere and devise methods of detecting the anthropogenic signal over the background noise of dec-cen climate variability.

The Atmosphere

Atmospheric water content (in all three phases), distribution of radiatively active gases, and aerosol concentrations all directly force the climate system and its principal operating agent, the atmospheric circulation. Atmospheric circulation plays a key role in redistributing physical and chemical properties, such as heat, moisture, and aerosols between source and sink regions, thus determining the regional variations of climate. In doing so, atmospheric circulation also directly controls the distribution in space and time of temperature and fresh water and thus the nature and distribution of ecosystems, surface radiation (via distribution of aerosols, which influence cloud distribution and formation physics), and sea level change (via distribution of heat and moisture and ice melt and decay). Atmospheric circulation, induced by fluctuating local and remote boundary conditions, also communicates changes from one location to another. This action often manifests itself in the form of storms. In addition, atmospheric circulation influences the location and disposition of large-scale climate patterns.

Issues in Atmospheric Circulation

Our current understanding of atmospheric processes and large-scale circulation suggests that one critical area of research is the feedback and interactions among moisture fields (clouds and water vapor) and motion fields. Particular issues are cloud-water vaporization feedback, cloud formation (including vertical structure, radiative, circulation, and other feedbacks), and the model representation of those processes, which often occur as subgrid-scale processes. Also important are the relationships of cloud formation and evolution and surface boundary conditions.

The relationship between atmospheric circulation variability and external radiative forcing has not been clearly resolved. Numerous studies have tried to identify periodic behavior in the atmospheric spectrum due to periodic changes in solar forcing. Because the lower atmosphere absorbs only a small part of incoming solar radiation, which varies by only 1 W/m^2 over a solar cycle, it is hard to see how such a weak signal could affect climate, unless a positive feedback existed in the atmosphere. Nonetheless, the evidence suggesting such a relationship is often compelling, justifying a concerted effort to understand the potential mechanisms.

Because of the likelihood that anthropogenic change is already imprinted in records of climate variability over the past century, there is a strong need to obtain paleorecords of past atmospheric conditions for instrumental and proxy data and to increase the volume of the archives through data "archeology" (reconstruction of past climate data) and additions of new data. These efforts should proceed in parallel with establishing clear guidelines for future atmospheric observations and careful planning of observational networks, so that adequacy, continuity, and homogeneity of the records are assured. The future observations should describe both state variables (winds, pressure, temperature, humidity, and rainfall) and forcing and other related variables (solar radiation, clouds, aerosols, and chemical composition).

Key Scientific Questions About Atmospheric Circulation

How much of the dec-cen variability is unforced? For example, are dec-cen variations of the PNA, NAO, and other climate patterns driven by inherent natural climate system variations, reflecting nonlinear internal interactions, or coupled interactions (in all cases, interactions that would effectively extend the intrinsic atmospheric timescales)? Or are the variations driven predominantly by changes in radiative forcing, due to anthropogenic increases of greenhouse trace gases, natural or anthropogenic aerosols, and/or variations in solar irradiance?

How does large-scale circulation change on dec-cen timescales, and how does it interact on these scales with regional and higher-frequency changes? Better documentation is needed of large-scale circulation changes to identify how they covary with regional climate states, storm tracks, and weather systems that typically vary over shorter timescales. In other words, how do variations in the mean climate state influence the spatial and temporal distributions of the higher-frequency variations, and how might this knowledge of the relationships help in predicting shorter-timescale climate phenomena?

What are the magnitudes, spatial and temporal patterns, and mechanisms of midlatitude atmospheric responses to both midlatitude and tropical SSTs? Numerous mechanisms have been hypothesized to explain the observed teleconnections between the tropical and extratropical latitudes, many involving the slow propagation of anomalies via ocean processes back to the equator and fast atmospheric processes away from the tropics. These and other such hypotheses must be thoroughly evaluated to identify the dominant mechanisms of anomaly persistence and communication. Also, the full spatial extent of such teleconnections has not been thoroughly documented. This information also must be pursued to determine over just what scales local and regional anomalies and influences are communicated. Moreover, links to tropical sea surface temperature and the decadal variability of ENSO were also drawn, as well as links to variations in the annual cycle of the southern hemisphere. The origin and maintenance of these phenomena and their associations must be the subject of considerable future investigations.

What are the mechanisms of interaction between the atmosphere and land surface processes on dec-cen timescales?

Through what mechanisms does the planetary boundary layer mediate between dec-cen variability of the surface boundary layer and the free atmosphere? One particular issue is how to average over short time- and space scales to study dec-cen processes, in particular boundary layer and interface processes.

What are the mechanisms of region-to-region and basin-to-basin interactions on the dec-cen timescale?

How do dec-cen changes in atmospheric trace gases and aerosols affect radiative balance and atmospheric circulation, and vice versa?

The study of decadal to centennial variability of atmospheric circulation faces many challenges. Much of our current understanding of the issue derives from the intense interest in anthropogenic climate change. This interest motivated efforts to reorganize the available instrumental and proxy data and to increase the volume of the archives through data "archeology" and additions of new data. These efforts should proceed side by side with establishing clear guidelines for future atmospheric observations and careful planning of the observational networks so that adequacy, continuity, and homogeneity of the records are assured (as discussed earlier). The observational efforts should focus on describing both state variables (winds, pressure, temperature, humidity, and rainfall) and forcing and other related variables (solar radiation, clouds, aerosols, and chemical composition).

Models of the climate system are powerful tools for the study of climate. Such models must be developed to allow the simulation of ocean, atmosphere, cryosphere, and changes in continental surface conditions. Representation of the processes controlling the evolution of all of these important components must be improved in atmospheric circulation models to properly evaluate the dominant interactions driving long-term climate change in the atmosphere.

The Ocean

The ocean influences the climate system through surface exchange, storage, and redistribution of heat, fresh water, and carbon dioxide. Because of its large mass and heat capacity, the relatively slow moving ocean is responsible for approximately half of the global equator-to-pole meridional heat transport. Regarding climate variability, the ocean's influence becomes increasingly important as the timescales of variability increase. At seasonal to interannual timescales, the ocean influences climate primarily through its large heat capacity in the relatively thin surface layer, whereas on longer timescales the heat transport over basin and global scales predominates.

Issues in Ocean Circulation

A key issue is the oceans' role in the longevity and long-term variability of climate patterns. Oceans are intimately tied to these patterns through SST and sea surface salinity fields. These fields typically covary with atmospheric surface layer pressure (SLP) fields, and an analysis of the nature of the covariation in the North Atlantic suggests a migration of SST anomalies along the primary circulation pathways of the North Atlantic. This finding suggests that upper-ocean heat content likely plays a main role in the survival of surface anomalies and their migration from year to year.

Unfortunately, climate patterns and their relationships with upper-ocean property fields are often difficult to evaluate because the empirical orthogonal function methodology most frequently applied for analysis tends to emphasize stationary patterns, precluding the identification of spatial migrations and covariability. This situation highlights the methodological inadequacies and thus the need to apply more complex tools (e.g., complex singular value decomposition) to allow the extraction of spatially propagating covarying field anomalies.

With the appropriate analysis tools, the first tasks are to identify clearly the oceanic and air-sea coupled signatures of these patterns, including their spatial and temporal linkages, and to explore data-poor regions to identify new patterns and better define existing ones. The relationships among ocean property fields and climate patterns must be more thoroughly documented and understood as well. Specifically, we must improve our understanding of how the ocean regulates, maintains, and otherwise influences these patterns and their evolution, particularly through its couplings with the atmosphere, sea ice, and land as well as through internal ocean mechanisms.

In addition to these general issues, a number of ocean-specific issues must be addressed. They concern the internal ocean processes that influence SST, the principal property coupling the ocean to the atmosphere and climate. Such mechanisms also control the storage and redistribution of heat, fresh water, and atmospherically active gases, which contribute to the atmospheric heat budget. Specifically, we require improved understanding and parameterizations of diapycnal mixing (mixing across density surfaces), surface layer processes, interbasin exchanges (including marginal seas, throughflows, and overflows), subduction and ventilation processes, and mesoscale processes to answer fundamental questions. How does subducted water (and anomalies in subducted water) mix and evolve as it flows around the subtropical gyre, and define the vertical density and circulation structure of this gyre? Can we quantify transport pathways and mixing from the time the water is subducted into the subtropical gyre to when it is re-exposed to the atmosphere at the equator?

Key Scientific Questions About Ocean Circulation

Dec-cen ocean issues involve defining patterns and mechanisms of the participation of the ocean in climate change. It is the formation and circulation of water masses that link surface forcings to the subsurface ocean. The variabilities of those water masses and forcings can alter subsurface ocean properties and circulation, and those subsurface changes can cause SST changes, locally or remotely, through advection, which feed back to alter the atmosphere.

- *What are the dec-cen patterns of ocean variability and what dynamical mechanisms govern them at dec-cen timescales?* The rich literature on organized patterns of atmospheric variability is not paralleled in ocean research. Correlations of SST and associated forcing fields with these atmospheric patterns have been partly explored, but recent efforts have revealed a propagation of SST anomalies indicative of transseasonal memory of winter conditions, in particular heat content anomalies and movement of the stored anomalies by advection. Much remains to be done in documenting these anomalies and their relationships to the subsurface property and circulation changes. Regional differences need to be explored. For example, the atmospheric fields associated with NAO and PNA (NPO) seem rather similar, but the participation of the oceans beneath their action centers may differ because of the presence of deep overturning in the North Atlantic.
- *What are the processes of formation and sequestering of water masses and of their subsequent modification and eventual return to the surface? What are their dec-cen variabilities?* How do anomalies of heat, fresh water, and chemical constituents translate into mixed-layer anomalies? How do the mixed-layer anomalies get into the ocean interior? How are they modified as they circulate through the interior and how are water masses re-entrained back to the mixed layer? How do freshwater fluxes (evaporation minus precipitation, sea ice, and runoff anomalies) modulate these processes through creation of salinity anomalies? Progress in

understanding the behavior of anomalies is inseparable from progress in understanding the processes maintaining the mean transports of heat, fresh water, and chemical constituents.

- *What are the dec-cen fluctuations of circulation structure and intensity and water mass pathways? How are they affected by surface forcing? What are the mechanisms of the fluctuations?* What are the relative roles, including the interaction of wind, thermal, and haline forcing? What are the surface expressions of these fluctuations? A number of processes are thought to modulate the intensity of meridional heat transport, as effected by gyre circulations and western boundary currents. These processes include eddy-driven (subbasin- and basin-scale) recirculations and the remote influence of wind stress and buoyancy anomalies via Rossby and coastal waves. What are the relative roles of these processes in dec-cen variability of heat transport and SST? What is the role of salinity advection feedback to surface freshwater anomalies when heat transport and SST anomalies exist?
- *What feedback and coupling mechanisms maintain SST, heat, fresh water, sea ice, and chemical anomalies on dec-cen timescales?* How do anomalies survive the seasonal cycle to reappear in subsequent winters, in particular, providing the observed long-lived recurrent winter SST anomalies? How do the histories of water masses evolve at higher latitudes, where sequestering is only seasonal, so that in winter there are recurrent advected heat content anomalies manifested as SST anomalies propagating downstream through the warm-to-cold water transformation pathways? What mechanisms control the strength, heave, and wobble of gyres on dec-cen timescales?
- *What are the mechanisms of region-to-region and basin-to-basin interaction on dec-cen timescales?* What mechanisms control the magnitude and other characteristics of waters exchanged among the oceanic circulation gyres and thus the amplitude and property fluxes of the full ocean overturning circulation? Can the variability of this overturning circulation be measured? Decadal change evidence focuses mainly on isolated gyre or paired gyre-gyre phenomena—do more global patterns and interactions occur on interdecadal to century timescales? Are there unique patterns for Southern Ocean participation in dec-cen climate variability, reflecting the circumpolar flow and linkages provided by the Antarctic Circumpolar Current, including the effects on adjacent basins' subtropical gyres? What are the processes connecting tropical SST and the extratropical Pacific? What oceanic processes modify ENSO events on dec-cen timescales?
- *How is carbon partitioned in the ocean and what are the roles of physical processes in the carbon flux?* What are the major processes controlling the partitioning of carbon among ocean reservoirs and between the ocean

and the atmosphere on dec-cen timescales? Can these fluxes be quantified? How can the capability be developed to predict the responses of oceanic biogeochemical processes to anthropogenic perturbations, as these responses relate to dec-cen climate change?

Several observational elements of a dec-cen ocean program must be directed toward elucidating the physics of key phenomena and processes to guide in their representation or parameterization in model simulations, should they not be fully resolvable in those simulations, and to provide a framework to interpret the decadal signals seen in the data and the models. Phenomena and processes need comparable concentrated efforts. For example, an examination is warranted of the special circumstance of mode water formation in the subtropics because it contributes so much of the thermocline volume and because it occurs adjacent to strong current systems, which account for most of the heat released from the ocean to the atmosphere.

Time series stations must be continued and supplemented. Discontinued stations should be reinitiated and new ones established. Sparser happenstance measurements provide limited gap filling for the interrupted stations and a background history for new sites. Improving on ship-based observations, new time series can use moored profiling conductivity-temperature-depth capabilities now coming online and subsurface floats, thereby reducing the need for ship-based support measurements. Continued satellite data are needed for global coverage of sea surface height, SST, winds, and ocean color, calibrated against in situ ocean observations.

The Cryosphere

The part of the Earth's surface that remains perennially frozen, as well as the part that is near or below the freezing point, constitutes the cryosphere ("cryo" means cold or freezing), though our working definition of the cryosphere is all forms of frozen water on the land or sea surface, whether admixed (as in permafrost) or pure (as in snow or ice). Thus, this section addresses not only glaciers and sea ice (perennial and seasonal) but also vast areas of frozen ground and permafrost, as well as seasonal snow fields that lie beyond the limits of glaciers.

Cryosphere Issues

The cryosphere directly influences climate through enhancing the equator-to-pole thermal gradient by increasing the albedo (radiation reflected from the surface) of the polar regions through vast areas of highly reflective ice and snow fields. The cryosphere also plays a predominant role in sea level; the most vulnerable ice sheet susceptible to potentially rapid destruction is the West Antarctic ice sheet, which contains enough water to raise sea level by 18 m should it melt.

Several of the major climate patterns, for example, the PNA and NAO, extend well into the polar regions (focal points of the cryosphere). Variations in the indices describing these patterns seem to be dominated by changes in the low-pressure systems in the northern extremes of these patterns. That is, changes in the Aleutian Low influence the PNA index, and the Icelandic Low influences the NAO index. These influences reflect the fact that the subpolar low appears to be less stable than the rather statically positioned, midlatitude, high-pressure ridges that control the indices' other limits. These low-pressure cells show considerable migration and variability in strength. Since they extend well into the polar regions and show some dependence on the regional SST at their lower surfaces, we might expect that they will show some dependence on the ice and snow distributions as well. The overlap also allows the patterns to bridge the high- and midlatitude zones, representing an obvious avenue through which coherent climate variations and change may be propagated between these latitudes. Also, some preliminary model studies[57] suggest that the modeled anthropogenic greenhouse distribution of surface warming differs from a natural pattern associated with the COWL distribution only with the former extending farther into the polar regions.

Previously, analyses of climate patterns neglected the polar regions, owing to the paucity of data on those locations. However, recently released historical Russian and U.S. data now allow inclusion of these regions into such analyses. It is thus now possible as well as important to identify the polar contribution and signature to these patterns. It is also essential to identify the sensitivity and dependencies of the patterns on crysophere characteristics, particularly the fairly mutable and mobile sea ice cover and snow fields. Finally, because the Antarctic Circumpolar Wave and its covariation with ENSO seem to suggest a hemisphere-wide teleconnection between the tropics and extratropics in the poorly examined southern hemisphere, we need to refine our understanding of the extent, nature, linkages, and controls of the Antarctic Circumpolar Wave with regard to extrapolar climate patterns (and climate in general).

In addition to issues related to climate patterns, a number of issues must be addressed to understand the nature and importance of cryosphere components in the global climate. Specifically, we need to determine parameterizations and sensitivities of the processes controlling several phenomena: (1) ice-albedo feedbacks, including spatial averaging of heterogeneous conditions; (2) snow-climate feedbacks, which are much like ice-albedo issues but for vast continental areas; (3) ice-cloud feedbacks; (4) ice-ocean feedbacks, including thermohaline circulation instabilities and interactions, surface stability influences, and ocean-ice interactions; and (5) ice sheet-ocean feedback and ice sheet instabilities.

One finding of tremendous interest in the past decade was the discovery that the ocean can generate an internal mode of variability over a variety of timescales. The nature, vigor, and characteristics of this variability are sensitive to the boundary conditions in thermohaline source regions, which are in the high latitudes and subject to cryospheric influences. We must better understand the role of heat and salt fluxes in this deep and intermediate circulation and, similarly, the contribution of local and regional ocean-ice-atmosphere feedbacks.

Finally, given the direct influence of ice mass balance on global sea level, better knowledge is needed of ice sheet mass balance and subice shelf melting, which today are poorly understood. Specifically, the current rate of melting and sensitivity of melt rate to regional ocean-ice interaction and change need to be determined.

Key Scientific Questions About the Cryosphere

- *How do sea ice and snow fields change on dec-cen timescales and what is the relationship of these changes to atmospheric, ocean, and land surface patterns on dec-cen timescales?* For example, as noted earlier, the NAO and PNA extend into the Arctic, and their indices often reflect changes originating in polar low-pressure cells. Thus, it is important to determine the covariation between changes in the ice and snow fields and these patterns. Likewise, because sea ice has been implicated in thermohaline circulation changes on a variety of timescales, how do these two phenomena covary?
- *What mechanisms underlie dec-cen patterns of interaction between sea ice and snow fields and the atmosphere, ocean, and land systems?* Do regional or even local changes in surface divergence alter albedo, surface heat fluxes, and cloud formation enough to influence the Icelandic or Aleutian lows and thus the NAO and PNA? Do changes in the patterns of large-scale planetary waves or ocean circulation alter polar conditions so much that they in turn drive additional changes in other parts of the climate system? For example, could variations in NAO influence the volume of fresh water exported from the Arctic in the form of sea ice to influence thermohaline circulation significantly? Observational evidence supports this idea,[58] as do model experiments.[59] Also, thermohaline circulation is sensitive to surface buoyancy fluxes in the source regions. Such regions lie predominantly in the polar regions, where growth, decay, and spatial redistribution of ice play a dominant role in these fluxes and thus may play a dominant role in the formation processes. The ice in turn depends greatly on the stability of the underlying water column, a situation setting the stage for considerable feedbacks and interactions.
- *Through what mechanisms are changes in the cryosphere of the polar regions linked or teleconnected to midlatitude and tropical regions?* For example, model results suggest that changes in sea ice fields alter the nature of the Hadley Cell through their influence on the equator-to-pole meridional temperature gradient. Observations suggest that the Antarctic Circumpolar Wave covaries with ENSO and Indian Ocean monsoons

through mechanisms not yet understood. Changes in thermohaline circulation, which may be related to the surface freshwater balance associated with growth and transport of sea ice, can alter surface volume (i.e., gyre characteristics) in subtropical regions.

- *What are the history and current global budget of land-locked ice and snow and what are the primary mechanisms controlling this budget?* Given the direct impact of this budget on sea level, we must better quantify the mass balance of continental ice sheets, alpine glaciers, and permanent snow fields. In particular, the balance at the base of floating ice shelves is in considerable question, and whether the Greenland and Antarctic ice sheets are gaining or losing mass is still uncertain. These questions must be resolved. Knowledge of how the land-locked ice and snow budget has varied over time will give some indication of the range, rate, and rapidity of change experienced through natural variability. Several other phenomena are critical in this budget and also must be better understood: the melt and growth rates and dependencies at the base of floating ice sheets, as well as ice sheet drainage rate, as a function of sea level (which alters the grounding line and thus frictional retarding force to the flow), and the response of precipitation to cold-region climatic changes.

Observations critical for addressing these issues include long-term monitoring of surface salinity with SST, since salinity is the principal control on the density of seawater in high-latitude regions. Also, the sea ice fields themselves, including the motion fields and ice thickness, are required to determine the freshwater transports and buoyancy fluxes associated with the ice fields. Finally, consistent monitoring of iceberg calving and an observational system to determine basal melt or growth (e.g., temperature/salinity moorings across the floating ice shelves) must be established to measure the land-locked ice and snow budget.

Model parameterizations must be improved to better represent certain phenomena: (1) ice-albedo feedbacks, (2) snow-climate feedbacks, (3) ice-cloud feedbacks, (4) ice-ocean feedbacks, and (5) ice sheet-ocean feedbacks and ice sheet instabilities. Improved simulation of sea ice and snow distributions and related impacts also must be achieved.

Land and Vegetation

Land and vegetation influence climate through many means. Most notably, their geographic distributions relative to the oceans help define the nature of the climate pattern because their low heat capacity relative to the high heat capacity of the oceans leads to alternating cycles of surface response to the same atmospheric forcing. However, on decade to century timescales, the main influences of land and vegetation are through their influences on the carbon (and methane) cycle and through changes in surface albedo owing to land surface and land cover changes, natural or anthropogenic.

Land- and Vegetation-Related Climate Issues

Simple model representations of vegetation in general circulation models (GCMs) suggest that the main influence of vegetation in greenhouse warming, and the main issue in comparing preindustrial (natural) vegetation to industrial (cultivated) vegetation, takes the form of albedo. Most notably, dark forests show minimal winter albedo influence in response to snow cover, whereas the loss of such forests exposes large areas that suddenly influence albedo considerably during summer and even more so during winter in the presence of snow cover. Hansen et al. (1997) show this land-use shift to be the major contribution of vegetation changes to a doubled CO_2-induced warming, with vegetation changes accounting for approximately 25 percent of the CO_2 direct influence. Changes in land surface characteristics can lead to similar effects, realized mostly, again, through albedo. Vegetation and land surfaces also affect climate through the hydrological cycle, as discussed in the section on the hydrological cycle below.

At the present time, our knowledge is poor regarding the effects of different vegetation covers in climate change. We must improve even our most basic understanding of these effects.

Key Scientific Questions About Land and Vegetation

- *What are the effects of human activity and climate change on ecosystem structure and function?* From paleoclimatic records we know that natural vegetation responds to climatic change: individual species respond according to their climatic tolerances, and ecosystem compositions change as a result. Competitive and trophic interactions among species are thereby altered, redefining where organisms can survive and reproduce. The responses of organisms to climatic change will be greatly influenced by human land-use patterns and other anthropogenic influences. Associated with ecosystem structural changes are changes in the biogeochemical cycling of carbon and nutrients, in ways that remain difficult to anticipate. Finally, the distribution of disease-carrying organisms will change as part of ecosystem restructuring and redistribution.
- *What are the relative contributions of the different processes by which vegetation and soils store or lose carbon?* Vegetation and soils store three times as much carbon as the atmosphere or upper ocean, yet large uncertainties remain about the quantitative contributions of various processes. Forest regrowth in the northern hemisphere, related to changing

land-use patterns, or perhaps CO_2 and nitrogen fertilization or climate change, may have been an important sink over the past decades.

- *What are the expected future emissions of CH_4, N_2O, and volatile organic carbon compounds by soils and vegetation?* CH_4 production in soils depends strongly on moisture conditions. N_2O production is a product of denitrification processes in soils. The emissions of volatile organic carbon compounds (ozone precursors) are strongly species dependent. Changes in these emissions depend on a combination of ecosystem and climate changes.
- *How do dec-cen changes in land use and land cover affect land surface energy balance on dec-cen timescales?* The nature of land cover determines its reflectivity and is expected to change with changing climate and human activities. For example, a warmer high-latitude climate will favor the expansion of boreal forest into tundra-dominated regions, with a concomitant lowering of albedo. Desertification, which may have both human and natural components, leads to an increase in surface albedo. The thermal structure, moisture content, and dynamics of the atmosphere will be influenced by the partitioning between sensible and latent heat transferred from the surface.
- *How does vegetation influence the transfer of freshwater through the land surface on dec-cen timescales?* Stomatal opening governs the rate of evapotranspiration from the land surface. Increasing CO_2 will tend to reduce stomatal conductance, increasing plant water-use efficiency. More evapotranspiration results in a higher water vapor content of the atmosphere over land, more precipitation, and less runoff via rivers and groundwater flow.
- *How do changes in vegetation cover influence the loading and composition of atmospheric aerosols on dec-cen timescales?* Vegetation naturally emits aerosol precursors. The nature and amount of these emitted compounds depend on the species. Thus, the distribution of aerosol precursors will change as ecosystems and species respond to climate change and human perturbations. Biomass burning generates aerosols (particularly soot) that influence the regional radiation balance. Desertification produces mineral dust that is transported in the troposphere and exerts a regional radiative forcing. The distribution of these aerosols can be expected to vary on dec-cen timescales in ways related to climatic and human influences.

Hydrological Cycle

The hydrological cycle refers to the origin and fate of water through its many phases in the atmosphere, ocean, land, and biosphere. Water evaporates as vapor from the surfaces of both land and ocean, condenses in the atmosphere, precipitates back onto both land and ocean surfaces, and ultimately finds its way back into the atmosphere as vapor. It can sometimes reside in surface or subsurface reservoirs for hundreds or thousands of years, or longer, before completing the cycle.

Issues Regarding the Hydrological Cycle

The hydrological cycle is central to questions about the magnitude of global warming associated with an increase in atmospheric CO_2. Water vapor in the atmosphere is the primary greenhouse gas, and the amount of water vapor is a function of the hydrological cycle, which controls the rate through which water is evaporated into the atmosphere and precipitated out and thus the quantity of water vapor residing in the atmosphere at any particular time.

It is generally agreed that the addition of radiatively active gases into the atmosphere will warm the surface (the degree of warming is in dispute) and significantly speed up the hydrological cycle so that total global evaporation and precipitation should both increase. This prediction of change is one of the most consistent results of models simulating anthropogenic greenhouse warming (see detailed discussion in Chapter 10). Rind et al. (1996) suggest that a doubling of atmospheric CO_2 should increase precipitation and evaporation rates by approximately 10 to 15 percent, resulting in an increase of total atmospheric water vapor of 30 percent. Unfortunately, the global data do not exist to confirm or refute such predictions, and the models are likely inadequate for properly establishing the net change and distribution of water vapor in the atmosphere. Therefore, one of the primary issues for improved understanding of the hydrological cycle is achieving better knowledge and model representation of those processes controlling the rate, paths, storage, and redistribution of water vapor through the hydrological cycle.

In addition to improving model representations of this cycle, we must better document the change and distribution of water vapor in the atmosphere, particularly its vertical distribution. Considerable controversy surrounds the issue of vertical distribution, with one theory suggesting that increased moisture in lower levels of the atmosphere would be offset by decreased moisture levels in the upper troposphere, reducing surface warming (and thus its moisture increase) and cooling upper layers, thereby greatly reducing the net warming otherwise anticipated from an increase in total atmospheric water vapor.

Regarding patterns of climate variability, the hydrological cycle plays an unknown role. However, some observed covariations suggest that changes in the NAO and PNA directly influence precipitation in Europe and northwestern North America. Similarly, clear covariations are found between patterns of the tropical Atlantic SST dipole and those of rainfall and drought in the African Sahel and northern Brazil. Thus, it may be possible to make regional precipitation predictions based on knowledge of these pattern covariations. Clearly, improved documentation and understanding of these relationships are needed, including knowledge of the mechanisms that drive them and their sensitivities.

Obviously, the hydrological cycle controls much of the climate attributes of precipitation and water availability. It also directly influences sea level. If more precipitation falls as snow than is returned by evaporation (or by sublimation, the direct vaporization of snow cover), snow will accumulate, eventually forming glaciers that can account for considerable changes in sea level. In fact, aside from sea level changes associated with plate tectonic spreading rates, the largest changes in sea level result from the waxing and waning of continental ice sheets. During the last ice age, enough fresh water was removed from the oceans and stored in continental ice to lower sea level by more than 100 m. Even today, in our relatively moderate climate conditions, the return of fresh water to the oceans from melting alpine glaciers and possibly ice sheets is thought to be responsible for about one-half of the 20 cm sea level rise observed in this century. Also, runoff (and ice drift, discussed previously) can considerably influence high-latitude polar regions, where ocean surface salinity plays a predominant role in sea ice formation (and thus local albedo and freshwater transport, among other things) and deep/bottom water formation, which are natural avenues through which the hydrological cycle may influence climate over decade to century scales.

The role of vegetation in the hydrological cycle also must be vigorously investigated. Rind et al. (1997) show that, while the role of vegetation is fairly moderate in contributing to a doubled CO_2 warming, the impact of the warming on the vegetation itself can be dramatic. In their GCM simulation with interactive vegetation, the impact of increased atmospheric moisture content is particularly enhanced over land, driving considerable evaporation from the vegetation (through transpiration). The vegetation attempts to limit this drying by reducing transpiration through stomata closing. While this may succeed as a short-term survival tactic against dry conditions, in the long run it also reduces productivity and eventually destroys the vegetation (particularly at lower latitudes). This result is not revealed in simple GCM studies that do not include a treatment of vegetation strain response (such as the treatment that was used in the first IPCC assessment[60]), though it is indicated in impact studies (such as those used in the second IPCC assessment[61]). Thus, we must address not only the role of vegetation in the hydrological cycle but the responses and feedbacks of the vegetation as well.

Finally, rainfall is poorly and sporadically measured, and evaporation measurements are woefully inadequate. Development of global climatologies indicates that there is disagreement between them, so it is not surprising that regional series of rainfall data of reasonable quality exist for only a few places. It is becoming more and more important that proxy reconstructions of past rainfall data be made to set the climatic context for studying decadal variability of precipitation and evaporation. Such time series are particularly important for hydrological control issues, such as water resource management; present-day levees, dams, and reservoirs are often engineered on the basis of inadequately short records of flood levels, with dramatic examples of inadequate flood protection (e.g., the Folsom Dam and Sacramento River flood controls) owing to undersized levees.

A classic but still unsolved hydrology problem is how to follow the water from rainfall back to the atmosphere and ocean. Improved understanding of this most basic process, especially, in this context, on decadal and longer timescales, is of fundamental importance; we need to know how variations in this process influence decadal- to century-scale climate variations. Where and at what rate water re-enters the ocean and how precipitation and evaporation redistribute fresh water in the ocean's surface layer play essential roles in ocean salinity, which is the driving factor in high-latitude stability, influencing thermohaline circulation and shallow and deep subduction and ventilation. In short, the role of the hydrological cycle in ocean circulation is critical to understand but is currently poorly known.

Key Scientific Questions About the Hydrological Cycle

The roles of the hydrological cycle in the climate system must be better understood, including through model representation of the processes controlling the rates, paths, storage, and redistribution of water through the cycle. The Global Energy and Water Cycle Experiment (GEWEX) program studies the detailed land surface hydrology in major drainage basins; the Mississippi basin will be a primary U.S. focus, and concurrent land experiments are proposed for other parts of the world as part of the international GEWEX program.

- *What are the patterns and mechanisms of prolonged drought on dec-cen timescales?* Paleoclimatic records provide ample evidence of droughts that persisted for many decades to centuries in regions that experience more moderate conditions today. Dune fields that are now vegetated existed during the past 1,000 to 10,000 years; tree stumps are found in modern natural lakes; and long periods of slow growth are revealed in drought-sensitive tree ring records. All indicate that persistent droughts recurred throughout the past few millennia. The mechanisms that lead to the initiation and persistence of multidecade to multicentury droughts are not well known but likely involve feedbacks from vegetation and/or long-term persistent SST anomalies that influence the supply and delivery of moisture. Even the interannual to decadal droughts documented by instrumental records (such as the North American Dust Bowl of the 1930s and the killing droughts of the Sahel in more recent decades) lack a clear mechanistic explanation. A more thorough examination of the patterns of past hydrological variability and the testing of plausible mechanisms through focused observational and simulation strategies should lead to a better predictive understanding of this critical climate attribute.
- *How do the distributions of water vapor, precipitation, and clouds interact with surface boundary conditions and changes on dec-cen timescales?* The hydrological cycle plays an unknown role in producing and respond-

ing to patterns of climate variability. However, relationships between the state of these patterns and large-scale precipitation seem to covary, and thus it may be possible to predict regional climatic precipitation based on knowledge of the pattern state. This potential underscores the need for improved documentation and understanding of these covarying relationships, refining the nature of the correlation and establishing the mechanisms responsible for driving them and their sensitivities. In addition to improving the model representations of this cycle, we must also better document the change and distribution of water vapor in the atmosphere, particularly its vertical distribution. There is considerable controversy about this subject, with one theory suggesting that increased moisture in lower levels of the atmosphere will be offset by decreased levels in the upper troposphere, reducing surface warming (and thus its moisture increase) and cooling upper layers, thereby greatly reducing the net warming otherwise anticipated from an increase in total atmospheric water vapor.[62]

- *By what combination of remote and in situ observations can we measure the large-scale distribution of precipitation on dec-cen timescales?* Rainfall is clearly crucial for all societal and economic activities. It is also a major way in which dec-cen variability is expressed. Observed covariations suggest that changes in the NAO and PNA directly influence precipitation in Europe and northwestern North America, and there are clear covariations between the tropical Atlantic SST dipole and rainfall/drought in the Sahel of Africa and in northern Brazil, as discussed above. But rainfall is still poorly and sporadically measured. The existing global climatologies significantly disagree among themselves; not even a baseline of large-scale precipitation is in hand. The advent of satellite measurements has provided a global view of precipitation through radiative proxies, but the absolute calibration in translating proxy fields to precipitation is in doubt. In situ measurements help to quantify the proxy radiation satellite measurements and are crucial not only for determining the absolute calibration of the satellite measurements but also for providing gradient information. The in situ and satellite measurements must be carefully combined to provide the optimal estimate of large-scale fields of precipitation. For measurements on dec-cen timescales, the combined remote/in situ measurement system must be designed to assure long-term consistency and accuracy, and this implies a commitment to long-term intercalibrated measurements.
- *What are the spatial and temporal changes in land storage of water and the pathways and fluxes of land water to the oceans?* The buoyancy state of the ocean (temperature and salinity) determines the water transformation properties of the ocean, the degree to which it produces deep and bottom water, and, ultimately, therefore, the transport properties of the

ocean and the stability of its internal oscillations. Crucial to these processes is the amount of freshwater input (directly through precipitation over the ocean and indirectly through runoff, groundwater discharge, and discharge of glaciers and other forms of land snow and ice, whether through rivers or ground discharge) and the geographic distribution of such inputs. The geographic distribution depends on the locations of rivers, the relative flows of the rivers, and the amount and distribution of groundwater discharges. These inputs are in turn determined by the relative precipitation and evaporation in the basins from which rivers and groundwater discharge into the ocean. Once fresh water reaches the ocean, it contributes to the salinity of the ocean, its sea level, its level of ions (especially from calcium carbonate) and salts, and its regional temperature. After undergoing mixing and advection, the ocean responds to salinity by altering buoyancy state and water mass transformation properties.

Climate models suffer from a lack of precipitation data through which they could be evaluated. In fact, precipitation on both large and small scales and the fate of hydrometers ejected from clouds in the upper atmosphere (which evaporate to become vapor rather than fall as precipitation) are crucial processes for the hydrological cycle in climate. Additional understanding is needed of evapotranspiration, the dynamics of vegetative cover, the dynamics of soil moisture, and all their parameterizations. The correct simulation of land pathways and water storage is a difficult modeling problem, inasmuch as water pathways depend on conditions far more local than climate models can resolve now or in the foreseeable future. The detailed paths of water on land and the modeling of these pathways on the catchment level are major themes of the GEWEX program.

It is currently believed that discharges from the melting ice pack that covered the United States during the last glacial maximum had significant influence on the thermohaline circulation of the North Atlantic and therefore the temperature of the North Atlantic. Additionally, modulations by iceberg discharges (Heinrich events) were likely significant punctuations in the region's climate record throughout the glacial period.[63]

- *What are the patterns and mechanisms of the dec-cen droughts?* A gridded 300-year reconstruction of the Palmer Drought Severity Index has been developed from 388 precisely dated tree ring records[64] to indicate periods of regional drought. Although the 1930s proved to be the most extensive drought in this record, more localized records[65] indicate that droughts more intense and prolonged than the Dust Bowl have been present in the record. As recently as 1,000 years ago in the Great Plains, ancient dune fields, now covered by vegetation, were active, suggesting that the ability of this region to maintain vegetative cover without human intervention is marginal.[66] California also provides evidence of simultaneous droughts (to within unavoidable error of roughly 100 years) with those in the Great Plains.[67] Similar evidence supports extreme droughts in Patagonia during these common periods, suggesting a common global cause for these droughts. Even longer tree ring records from California, spanning several millennia, indicate periods of below-average rainfall lasting on the order of a millennium.[68] This record also indicates a recurrence of short-term droughts of greater magnitude and duration than any in the instrumental record of the past 100 years. Were such droughts to recur during present times in California, drastic consequences would ensue for a vulnerable and populous region.

Atmospheric Composition and Radiation Budget

While the atmospheric boundary conditions are essential for extending the timescales of climate variability, changes in the atmospheric composition and radiation budget, owing to internal, coupled, or external mechanisms, are directly responsible for determining the atmospheric temperature distributions in space and time. Consequently, variations in composition and radiation budget, and the direct and indirect consequences of these variations, are of critical importance.

Atmospheric Composition and Radiation Budget in the Climate System: The Issues

Atmospheric composition can change because of many factors. Among those of considerable current interest are changes due to the influence of humans, most particularly through the anthropogenic increase in atmospheric carbon dioxide, chlorofluorocarbons (CFCs) and other halocarbons, methane, nitrogen oxides (NO_x), and aerosols. Some of these gases, such as CFCs and halocarbons, have no known natural sources, so their influences are the direct result of anthropogenic change.

Each of these compounds plays a direct role in the atmospheric equilibrium temperature, and this direct influence is fairly predictable given any particular emissions scenario. However, more importantly, the indirect influence of increased gas and aerosol concentrations is not well known. For example, as discussed above, an increased direct warming is thought to drive an increase in the rate of the hydrological cycle, an influence that will have an uncertain net effect on the amount and vertical distribution of water vapor in the atmosphere. Since water vapor is the primary greenhouse gas, being able to predict its response to a direct forcing is essential.

In addition to the direct anthropogenic forcing, there are possible feedbacks in the atmosphere involving the natural system that must be understood. Most notable is the response of continental biomass, which can alter the rate and storage times of carbon in vegetation and thus either exacerbate CO_2, methane, and NO_x emissions or provide them an enhanced sink. Similarly, direct changes may alter ocean circulation and productivity, which can drive additional feedbacks. The direct influence of changes in the ocean productivity on atmospheric composition have been shown to be fairly small, but changes in the ocean circulation can introduce changes in the ventilation of deep waters, which contain approximately 50 times more carbon dioxide than the atmosphere, thus driving potentially larger feedbacks, though presumably on longer timescales. This kind of response implies a more gradual feedback process but a more persistent one as a result. That is, this influence may not be reversed quickly, regardless of short-term changes in direct forcing (e.g., in the emissions).

Changes in atmospheric composition, particularly additions of CFCs, also influence climate through their destruction of atmospheric ozone. This effect is particularly important to the vertical temperature distribution in the lower stratosphere. Such destruction also alters surface ultraviolet (UV)B radiation, posing a climatic change that has direct societal consequences as well (e.g., increased risk of skin cancer and alteration of at least some components of ecosystems such as the ocean plankton). While the chemistry of ozone response to a given concentration of chlorine and bromine is fairly well known, within our envelope of experience, one of the largest issues facing ozone destruction and recovery is the potential deviation of effects from the pattern of our current understanding—if there are continued large increases in CH_4 and H_2O, which may move us into chemical and physical regimes that are not clearly understood.

Changes in tropospheric ozone directly influence the Earth's radiation budget and thus directly influence climate change and variability. Of primary importance in this area is improved understanding of tropospheric chemistry models and improved representation of cloud-chemistry interactions.

Although carbon dioxide cycles quickly between the mobile reservoirs, it leaves that system only very slowly, through the burial of organic matter. Dissolution of calcite, also a very slow process, adds carbon to the mobile reservoirs but increases the carbon-holding capacity of the oceans even more. Therefore, future levels of atmospheric CO_2 depend on how the additional carbon from fossil fuel burning is partitioned between the mobile reservoirs, which can be considered an almost-closed system. Important factors are, foremost, the rate of fossil fuel consumption, followed by circulation of the ocean and its interaction with marine biological productivity (including the potential sensitivity of the biological pump at high latitudes), management of the land (including deforestation and the relationship between the ecosystem and CO_2 changes), and carbon storage by ecosystems, possibly stimulated by increased CO_2 and deposition of nitrogen. Climate change will affect all of the natural processes cited above, and considerable effort must be extended to understand these processes further, including their feedbacks and sensitivities.

Current representation of the processes responsible for partitioning of carbon among the mobile reservoirs is very crude and sometimes speculative and involves many assumptions. These models are best viewed as extrapolation tools, and their predictive powers beyond the next few decades are tenuous. Progress in understanding the driving forces of carbon storage on large spatial scales is especially hampered by the current inability to verify through observations how local processes and fluxes are extrapolated to large scales. For greenhouse gas management the highest priority is to learn more about the behavior and model representation of the terrestrial biosphere, since we exert considerable influence on it. A long sustained effort of observation and modeling, developed together, will be necessary. Uptake by the oceans needs to be closely monitored via repeated transects every 5 to 10 years and via measurements of the difference in CO_2 partial pressure (pCO_2) and isotopic ratio between the atmosphere and ocean surface. With respect to the latter, actual measurements of air-sea exchange flux over the open ocean would lead to a much better parameterization of the exchange process.

The injection of volcanic aerosols affects climate through stratospheric cooling (but warming in the tropics), lowering planetary albedo, and increasing surface area for chemical reactions that influence ozone levels, among other things. In fact, with respect to the latter, it has been demonstrated that changes in ozone cannot be properly interpreted without consideration of stratospheric aerosol loading. Volcanic eruptions and their stratospheric effects are necessarily unpredictable in occurrence and magnitude. Since the role of volcanic aerosols in climate and particularly their role in ozone trends is complex and perhaps longer lived than is generally understood, it is crucial to maintain the capability to depict global stratospheric aerosol loading (especially in terms of surface area density) with high vertical resolution.

Finally, the Sun is the driving force of climate, and even small variations in the amount of energy that the Earth receives can have significant impact. In general, a doubling of CO_2 generates a radiative forcing that is equivalent to a 2 percent increase in solar irradiance. The changes in climate over the past several centuries are much smaller than expected from such a change, and we expect decade-to-century changes of about 0.25 percent. The relationship between solar wind and solar irradiance has been calibrated for the last solar cycles. Extrapolation for conditions outside this range, if applicable, would imply a decadal to century variability in solar irradiance with periods of lower irradiance by as much as 0.25 percent. The major difficulty in hindcasting solar irradiance over the past several centuries is the use of solar activity indices as surrogates for solar irradiance. Better understanding of solar physics and modeling of the solar cycle and the Earth's climate would allow greater confidence in this connection.

Key Scientific Questions About Atmospheric Composition and Radiation Budget

Greenhouse Gases

- *What are the changes in the spatial distribution of carbon storage and flux on dec-cen timescales?* Of the carbon emitted by anthropogenic activities in the past two centuries, just over half of that has remained in the atmosphere. Nearly half has been taken up by other mobile reservoirs, the biosphere, and surface ocean. Although initial estimates of carbon sinks failed to account for a large fraction of anthropogenic CO_2 emissions, recent calculations suggest that a growing terrestrial biosphere may account for this "missing sink." Uncertainties in estimates of biospheric activity, together with poor knowledge of the surface ocean's uptake, suggest that our knowledge of the fate of anthropogenic CO_2 may not be inaccurate. Atmospheric CO_2 has been increasing steadily since the mid-1800s, but interannual to decadal fluctuations in the rate of rise also are seen in the atmospheric record and may be due to biospheric or oceanic variability. Predictive knowledge of atmospheric greenhouse gas concentrations requires that we narrow the current uncertainties in evaluations of carbon sources, sinks, and fluxes.

- *How do mixed-layer water replacement rates interact with biological processes to produce changes in ocean carbon storage?* The biological pump—that is, the sequestration of inorganic carbon by primary productivity in the surface ocean—virtually determines the partitioning of carbon between ocean and atmosphere. Without the biological pump, atmospheric concentrations of CO_2 would be three to four times higher than they are today. The biological pump delivers carbon to the deep ocean, which exchanges with the atmosphere on timescales of centuries and longer. The pump's level of activity depends on the extent of nutrient utilization, which can change as a consequence of changing vertical mixing rates. The latter rates can alter both nutrient supply and the time available to surface phytoplankton to utilize these nutrients.
- *What are the uptake, pathways, and fate of anthropogenic carbon in the ocean on dec-cen timescales?* In addition to the "biological pump" of carbon described above, the surface ocean takes up CO_2 passively through gas exchange. The exchange of CO_2 between atmosphere and surface ocean occurs partly as a function of the atmosphere-ocean concentration gradient; thus, as atmospheric CO_2 rises from anthropogenic inputs, the ocean gas-exchange sink strengthens. Current best estimates of the oceanic uptake of anthropogenic CO_2 derive from numerical models. The paucity of accurate observations is still a significant obstacle to the quantification of oceanic carbon uptake and its pathways.
- *What are the contributions of various sources and sinks to the recent increase in methane?* Although observations document that atmospheric CH_4, a potent greenhouse gas, has increased steadily since the nineteenth century, the causes of this rise are not sufficiently quantified. Likely candidates for the new sources include expanding agricultural wetlands and livestock herds, biomass burning, fossil-fuel-related industry, and landfills. The total quantity of methane added to the atmosphere is well

known from the atmospheric rise, but the contributions of individual source components are not. Surprisingly, the main sink for methane, oxidation by tropospheric OH, appears to be stable over at least the most recent decade.

- *How does the photochemical breakdown of methane contribute to other chemical and radiative processes in the atmosphere on dec-cen timescales?* The photochemical breakdown of CH_4 consumes OH and produces water throughout the atmosphere; in the stratosphere even small amounts of water vapor are extremely efficient contributors to the global greenhouse effect. Thus, dec-cen changes in methane can be expected to alter the vertical distribution of water vapor in the higher troposphere and lower stratosphere, thereby changing radiative forcing. The ice particles that form at these altitudes also provide sites for heterogeneous chemistry. The feedbacks among these chemical processes and atmospheric dynamics are largely unknown.
- *Why is N_2O increasing on dec-cen timescales?* Records of atmospheric N_2O show a steady rise since the nineteenth century, but a quantitative budget of N_2O sources and sinks that explains this rise cannot be developed from the existing scarce observations and limited understanding of processes. The global nitrogen cycle has been heavily altered by human activities, particularly by the widespread application of high-nitrate fertilizers. Processes related to soils have likely been more disrupted by recent human activity than oceanic denitrification/nitrification rates. Industrial N_2O production also is a likely cause of the recent increase.
- *Why has tropospheric ozone increased since the nineteenth century and are further increases likely?* What are the controls on the abundance of tropospheric ozone? To what degree are precursors, photochemistry, transport, and dilution important? Although trends over recent decades are unclear, tropospheric ozone has almost certainly increased substantially since the last century. Because ozone is a pollutant with documented health and ecosystem impacts and a greenhouse gas, we need to be able to predict its concentrations. Knowing the interactions among precursors, transport, and photochemistry also is critical.

Stratospheric Ozone

- *How does the coupling between chemistry, dynamics, and radiation in the lower stratosphere and upper troposphere operate on dec-cen timescales?* For example, what do we need to know to predict the timing of ozone recovery accurately? How do changes in the stratosphere affect atmospheric circulation and the surface radiation balance? Ozone distribution influences the vertical temperature structure and dynamics of the lower stratosphere because of its absorption of UV radiation. These dynamics in turn determine the distribution of other atmospheric constituents, including ozone and their chemical interactions, in the upper troposphere as well as the lower stratosphere. Human impacts on these coupled processes include a potential future fleet of high-flying aircraft and changes in the sources of ozone-destroying halogenated compounds. The feedbacks among human influences, chemical interactions, and atmospheric dynamics are largely unknown. The most serious uncertainties for prediction of ozone recovery during the next century may be potential changes in the chemistry and circulation of the stratosphere that put us well outside current experience. Such changes might include continued large increases in CH_4 and stratospheric H_2O or stratospheric circulation changes associated with global warming and greenhouse gases. The predictive models are based in part on first-principle physics and chemistry and should correctly account for these changes, but we must recognize that observations of the recent past are used to test and calibrate models.

Aerosols

- *How do the spatial distribution, chemical composition, and physical properties of aerosols vary on dec-cen timescales and how do they interact with climate variability?* How do the composition and properties of aerosols determine their radiative effects? What are the regionally varying impacts of aerosols on the Earth's radiation budget? How do aerosols contribute to cloud formation, precipitation, and radiative interaction? While aerosols appear to present a critical radiative forcing on dec-cen timescales, the mechanisms and processes of this forcing remain poorly characterized. For example, the composition and properties of aerosols determine radiative effects in ways not yet well documented. The direct (reflective) effects of aerosols may change or reverse over high-albedo surfaces, where radiation absorption can contribute to overall atmospheric heating rather than cooling. The indirect effects of aerosols, related to cloud formation and radiative interactions, remain a major uncertainty but in fact may represent aerosols' primary impact on climate. Predicting future aerosol impacts requires understanding regional sources and transports and how these may vary with future climate scenarios. Human-initiated changes (e.g., through industrial emissions, biomass burning, and land use) are a key component in anticipating future aerosol variations; natural sources may be even less predictable (e.g., volcanic eruptions and natural vegetation emissions).

Solar Radiation

- *How do proxies for solar activity (e.g., sunspots, cosmogenic nuclides) relate to total solar irradiance on dec-cen timescales?* Direct measurements of the Sun's radiative output span only the last solar cycle. Solar radiation appears to correlate well, however, with solar activity as represented by sunspot variations, solar wind intensity, and charged particle fluxes. Reconstructions of solar activity that span nearly the past 400 years can be derived from records of cosmogenic nuclides (e.g., ^{10}Be) and historical sunspot observations. Extrapolated from measured relationships over the past solar cycle, these reconstructions indicate variability in solar radiation of 0.25 percent over decade to century timescales. The sensitivity of climate to these variations has been explored using observational data and climate models, but it is still not fully known how well the solar proxies represent irradiance. For example, while sunspot observations failed to indicate activity during the Maunder minimum (1600 to1640 AD), ^{10}Be records continued to show relative changes. A better understanding of the Sun's influence on dec-cen climate variability requires improving reconstructed solar irradiance.

- *What feedbacks govern climate and ecosystem responses to spectral changes in solar irradiance on dec-cen timescales?* Although the part of the solar spectrum likely to have greatest climatic influence lies in the visible range, the decadal solar variability observed over the last solar cycle occurs primarily in the UV range. Variations in UV have demonstrable effects on stratospheric O_3 levels and on atmospheric electricity, the last of which may influence cloud droplet nucleation. UV variability may also influence temperature patterns in the middle atmosphere, which affect the surface by altering how planetary waves propagate energy. UV changes can also impact ecosystems, particularly primary producers in both marine and terrestrial realms. The influence of UV on climate and ecosystems is poorly understood but must be considered in any evaluation of the Sun's influence on the Earth system over dec-cen timescales.
- *To what extent are dec-cen climate changes, as observed in instrumental and paleoclimate records, related to changes in the Sun's output and what mechanisms are involved in the response of climate to changes in solar radiation?* Decadal variations occur in most records of climate that have sufficient length and resolution, but the degree to which these fluctuations can be attributed to solar variability has prompted significant debate. Even studies that point to apparently distinct influences of solar variability on climate sometimes indicate highly variable sensitivities for a given irradiance change. Feedbacks within the climate system, particularly in the atmosphere, may enhance or dampen the climatic response to solar forcing. Understanding the sensitivity of Earth's climate to past changes in solar activity will enable better predictions of future changes in the face of decadally varying solar irradiance superimposed on other radiative forcing trends.

LESSONS LEARNED

The Extent of Natural Climate Variability

Findings of the paleoclimate community have shown the large degree of natural climate variability present in the climate record on many timescales. The impressive and often abrupt swings in climate recorded over the past several thousand years, such as the Little Ice Age, may if anything understate the potential for natural climate variability. We have learned that the climate of the Holocene has been relatively tranquil by the standards of Earth history. Our heretofore implicitly accepted tenet that we live in a relatively stable climate system has been completely undercut. We cannot base future climate-related policies (e.g., water resources management) on present-day climate conditions. With or without anthropogenic greenhouse warming, we must recognize the potential for the Earth's climate system to change, over a human lifetime, in ways that may have direct and important consequences on society and people's quality of life.

The Human Capability to Change the Global Environment

The past decade has demonstrated unambiguously that the global environment has been altered by human activities. The increase in atmospheric CO_2, the changes in tropospheric and stratospheric ozone, and the secular rise in sulfate aerosols in the troposphere all have been clearly tied to human activities. Detection and attribution of an anthropogenic signature in global climate have proven to be more difficult issues. While the balance of evidence points to an anthropogenic influence on climate,[69] the unique and unambiguous detection of this signature remains an area of active research.

The Unique Paradigm of Decadal to Centennial Climate Research

The growing experience with decadal to centennial climate studies has shown that, while much can be learned from the seasonal to interannual experience, there are fundamental differences in how the two sets of problems must be approached. Decadal- to centennial-scale studies, unlike efforts addressing the shorter term, such as weather forecasting and ENSO prediction, suffer from the absence of any easily realized iterative cycle of prediction and observation. This drawback has emphasized the importance of using paleoclimate records to hindcast and of calibrating instrumental records to detect potentially subtle long-term changes. The use of anomaly models that assume a constant background mean state, so productive in ENSO studies, is inappropriate for longer model runs, where change of the background state is the result of interest. Finally, a far larger range of processes is important in dec-cen studies. Radiative forcing, cloud interactions, involvement of the deep ocean, and sea ice dynamics are but a few of the processes that will be major influences on the long-term evolution of climate. Process studies are thus of particular importance for prediction. The influence of processes must be modeled correctly for there will be no opportunities to test them through direct short-term observations of today's climate system.

RESEARCH IMPERATIVES: PRIORITIES FOR OBSERVATIONS, MODELING, AND THEORY

As elaborated in the discussion above, the following Research Imperatives are required to advance most efficiently our understanding of dec-cen climate variability and change:

- *Natural climate patterns.* Improve knowledge of decadal- to century-scale natural climate patterns, their distributions in time and space, optimal characterization, mechanistic controls, feedbacks, and sensitivities, including their interactions with, and responses to, anthropogenic climate change.
- *Paleorecord.* Extend the climate record back through data archeology and paleoclimate records for time series long enough to provide researchers with a better database to analyze decadal- to century-scale patterns. Specifically, achieve a better understanding of the nature and range of natural variability over these timescales.
- *Long-term observational system.* Ensure the existence of a long-term observing system for a more definitive observational foundation to evaluate decadal- to century-scale variability and change. Ensure the system includes observations of key state variables as well as external forcings.
- *Climate system components.* Address those issues whose resolution will most efficiently and significantly advance our understanding of decadal- to century-scale climate variability for specific components of the climate system.
- *Anthropogenic perturbation.* Improve understanding of the long-term responses of the climate system to the anthropogenic addition of radiatively active constituents to the atmosphere and devise methods of detecting anthropogenic phenomena against the background of natural decadal- to century-scale climate variability.

The foundation for recent progress in ENSO research was laid by Rasmussen and Carpenter's (1982) careful diagnosis of ENSO pattern variability. Similarly, understanding and predicting decadal to centennial variability depends, to a large extent, on knowledge of climate patterns on these longer timescales. Logically, we might expect that the response of the Earth system to anthropogenic forcing could be manifested in and/or obscured by these patterns. Thus, one particularly important concern is the interactions between natural variability and anthropogenic change.

For greater predictive capability it is essential to understand those processes operating in the various components of the climate system that are relevant to dec-cen variability. Because of the difficulty of directly observing phenomena of interest in dec-cen studies, in contrast to weather or seasonal to interannual studies, the importance of component process understanding is magnified.

Regarding anthropogenic perturbation, it is particularly important that we closely monitor the rate and distribution of source functions of the radiatively active gases being added to the atmosphere. These external forcings, which cannot be predicted prognostically, can then be properly introduced and diagnosed in the predictive model studies. Such models are our primary means of forecasting anthropogenic change and of guiding diagnostic and attribution studies and sampling efforts. It is therefore critical to adopt an incremental long-term observing system whose characteristics and targeted variables can evolve in parallel with our rapidly improving understanding.

Many of the issues defined here require observing systems that do not yet exist or to which no long-term commitment has yet been made. An example of this need is the monitoring of solar irradiance: current data have come from relatively short-term satellite missions that have no operational (long-term) mandate (see case study in Chapter 8). Measurements from different missions are significantly offset. Addressing decadal to centennial solar variability, as discussed above, requires a plan for long-term calibrated solar irradiance measurements across the solar spectrum.

Finally, as previously indicated, dec-cen research is in its early stages, with new insights, findings, and directions arising at an impressive rate. Likewise, the long-term sampling strategy and optimal measurement set are evolving with these advances as well. At this stage, then, it is essential that we begin (or in a few cases continue) consistent monitoring of the most fundamental state variables (e.g., atmospheric temperature and moisture profiles, ocean surface temperature and salinity values), and monitoring of those variables specifically relevant to climate system components to initialize (including via assimilation), force, and diagnose model components and variables.

Atmospheric Observations

The Physical System

The physical state of the atmosphere, regardless of the mechanisms influencing this state, is at the very core of what we call climate. Atmospheric temperature and moisture content, pressure, winds, and cloud cover (the main factor controlling surface radiation balance) must all be monitored. The spatial distribution of this monitoring can be improved with time to span the globe eventually at the relevant spatial scales, but initially a concerted effort must be made to monitor these variables at current weather station locations.

As the concentration of greenhouse gases increases in the atmosphere, the atmosphere clearly must respond in some manner to accommodate the change in radiative forcing. The atmosphere may respond by warming to some degree, it may change its vertical distribution of moisture and cloud cover, or any combination of these may occur. Each of the state variables must be monitored, including their vertical distributions through the troposphere and lower stratosphere, to evaluate the nature of anthropogenic and natural changes. One of the most hotly debated topics in modern climatology is how atmospheric moisture distribution will change in response to the addition of greenhouse gases and therefore whether, or by how much, this moisture response will moderate the temperature response. Thus, it is not enough to measure temperature, simply because temperature has been the initial focus of the greenhouse debate.

Atmospheric observations must be colocated with those stations established to monitor surface conditions. This need directly follows from the earlier point that most, if not all, dec-cen atmospheric variability and change are in response to changes in slower components of the climate system, such as land, ice, and ocean. These components represent the lower boundary of the atmosphere. In many cases, as noted above, atmospheric changes strongly covary with changes at the surface. To evaluate, diagnose, and attribute dec-cen change, such covariation must be captured in a manner that facilitates analysis and evaluation of hypotheses that describe the coupled mechanisms driving and modulating long-term variability.

Process studies and related field efforts must be directed to improving our understanding and parameterization of surface-atmosphere interaction. Obviously, it is through this boundary interaction that slower-scale components communicate their influences to the atmosphere. Thus, appropriate parameterization of these phenomena are essential, since modeling efforts are the primary tool we have for forecasting future change. We also need better parameterization of clouds, including distribution and feedback processes, since their treatment in models may prove crucial in predicting long-term climate responses to changes in radiative forcing, as well as other feedback influences associated with variability and change. These parameterizations are currently a primary limitation in existing models.

The Chemical System

The radiative effects of aerosols, direct and indirect, are poorly constrained. Cloud processes, although they occur on far shorter than decadal timescales, are a major uncertainty in predicting future radiation balances. Parameterizations need to be improved.

Carbon cycle questions require a CO_2 measurement strategy that accounts for the hierarchy of scales, both temporal and spatial, inherent in ecosystem processes and their controls. Atmospheric concentration data must allow the identification and quantification of regional sources and sinks and their responses to climate fluctuations and human perturbations. This information will permit integration over regional scales of fluxes and feedback processes that can be measured, understood, and modeled on smaller spatial and temporal scales. Isotopic data allow distinguishing between oceanic and biospheric sinks on regional scales and have provided significant insight into the regional carbon balance. Ratios of O_2 to N_2 in the global atmosphere provide an independent constraint on the balance between net terrestrial and oceanic sinks. The same scaling and measurement issues are almost identical for N_2O and CH_4, and their biogeochemical budgets can be tackled together with a measurement program suitable for CO_2.

Enormous progress in assessing trace gas budgets could be achieved if a method could be developed or refined to directly measure air-sea gas exchange rates. Promising methods are air measurements with eddy correlation and/or eddy accumulation. Such measurements would eventually lead to a realistic understanding of the processes controlling the rate of gas exchange and therefore to a parameterization that could be applied with confidence worldwide. Existing climatologies of the partial pressure differences between the air and the water for many gases could then be turned into maps of gas exchange, making oceanic data into a much more compelling constraint on the atmospheric budget and closing the open boundary of surface oceanic gas budgets.

Ocean Observations

Various types of ocean observations are needed to study the dec-cen variability associated with the primary known patterns of atmospheric climate variability: periodic (decadal) temperature, salinity, oxygen, and tracer sections; velocity profile surveys and repeat sections (starting with World Ocean Circulation Experiment sections); and higher-frequency time series stations (starting with past and present weather ship stations). These measurements will allow better quantitative description of the ocean's participation in that dec-cen variability, especially in light of the slowly propagating SST and subsurface anomalies that have revealed the ocean's dec-cen variability as more than stationary patterns. We must extend these surveys into southern hemisphere regions as the nature of the dec-cen variability begins to be revealed.

These sections and time series stations provide the baseline against which the long-term response and change of the ocean can be measured and the basic observational set from which serendipitous discoveries about the ocean's role in climate change have been realized. In addition, the time series data have been invaluable in studying the ocean's response to atmospheric forcing and its feedback to the atmosphere. These findings are of particular importance because surface layer interaction and response dictate the volume of water in direct communication with the atmosphere. Even a small change in this volume can lead to a significant change in SST, given the same magnitude of surface forcing. The time series stations are the only series available that allow appropriate development, diagnosis, and improvement of these parameterizations.

Continued satellite data are needed for global coverage of sea surface height, SST, winds, and ocean color, but for these data to be useful, corresponding ground-truth ocean observations also are needed. Particular data of interest concern the heat budget. A concerted effort is required to improve estimates of heat flux divergence and heat storage and their variabilities from subsurface ocean data, eliminating disparities between those estimates and air-sea heat exchange estimates. Various subsurface floats and moorings are particularly helpful to supplement shipboard measurements for this study.

Sea level change is another important observational challenge. The IPCC (1996) estimates that in the year 2000 sea level will be 46 to 72 cm higher than today (36 to 53 cm, when the effects of sulfate aerosols are included). A range is given because each projection presumes a specific scenario for increase in greenhouse gasses. To validate these predictions, better monitoring of global sea level change and its components will be needed. The prospects for sea level monitoring are good. A global network of sea level stations (Global Sea Level Observing System) is being implemented. Land movements will be measured at some of these stations with satellite geodesy and gravimetric techniques. Satellite altimetry is another important tool coming into use to measure global sea level rise.

Cryosphere Observations

Critical cryosphere-related observations for climate patterns on decadal to centennial timescales include long-term monitoring of surface salinity along with SST, since salinity represents the dominant control on the density of seawater in high-latitude regions. Also, measurements of the sea ice fields themselves, including motion fields and ice thickness, are required to determine the freshwater transports and buoyancy fluxes associated with the ice fields. This freshwater transport has been implicated in driving major changes, even mode shifts in the global thermohaline circulation. Finally, consistent monitoring of iceberg calving and an observational system for determining ice basal melt or growth (e.g., through temperature/salinity moorings across the floating ice shelves) must be established to better determine the freshwater budget. Both field and satellite studies are needed to refine the mass budgets of the Greenland and Antarctic ice sheets. Onsite studies that focus on ice flow, melting, and calving should be continued and extended. Water vapor flux divergence observations will help pin down the source of the ice sheets' mass. A laser altimeter on a polar-orbiting satellite is needed to augment existing radar altimetry. These satellite data will provide accurate estimates of ice sheet volume and give early warning of possible ice sheet collapse. As in the case of ice, the distribution of snow fields, including thickness and spatial extent must be monitored. The response of snow distribution to climate change has been hypothesized as being important in surface-climate feedbacks as well as in climate change diagnostics.

Finally, the ocean-atmosphere-ice interaction, particularly the ice or snow surface energy balance (including surface albedo and ocean-ice, ice-cloud, and snow-cloud feedbacks), must be addressed through detailed process studies to improve parameterizations of these processes in climate models.

Land and Vegetation Observations

As explained in sections above, it is also essential to monitor changes in land surface characteristics, including surface vegetation. These changes alter not only the distribution of surface reservoirs and the surface-atmosphere exchange of radiatively active gases but also albedo and even surface stress and evapotranspiration efficiency—and the last two both influence the hydrological cycle. This serves as an external forcing to the planet that cannot be predicted and must be introduced into the models as they occur to properly maintain the models' surface forcing conditions.

Long-term monitoring of near-surface aerosol distributions also is needed. These distributions may induce stationary changes in the surface radiation balance, which may lead to large-scale circulation moderation through stable gradient perturbations.

Hydrological Observations

Precipitation is the key hydrological variable. For most studies of dec-cen variability and its effects, global fields of precipitation over timescales of 10 to 100 years are essential. We have no such global instrumental records currently. The National Aeronautics and Space Administration's Tropical Rainfall Monitoring Mission is an important first step, but global data are needed. To relate precipitation to global boundary conditions, SST, vegetative ground cover and soil moisture, and sea and land ice and snow must be simultaneously measured. Nearly every theory of anthropogenic warming finds an increased rate of the hydrological cycle and possible alteration of atmospheric distributions of moisture and of the frequency, intensity, and distribution of rainfall (including severe rainfall events). Thus, monitoring of the surface distribution of precipitation and evaporation must begin. This monitoring includes that over the oceans, where changes in the precipitation minus evaporation balance alter the surface salinity budget, which in high latitudes has been implicated in altering the thermohaline circulation (and driving internal oscillations on dec-cen timescales in ocean models).

CONCLUSIONS

Above we observed that the dec-cen paradigm must differ from that used to study shorter-timescale variability. Moreover, even the nature of the observations collected for dec-cen studies must differ. While, for example, atmospheric state variables must be monitored in both cases, because the diurnal and seasonal cycles in these variables are often so large, they virtually swamp any longer-term, more slowly evolving timescale changes as they are taking place. Thus, short-term climate change can often be identified using relatively coarse sampling resolution (and accompanying precision and accuracy); if longer-term change is to be detected using relatively short time series, these measures require considerably higher resolution (and precision and accuracy). How much higher changes with the variables measured and the rate at which the dec-cen change occurs. However, in any case, care must be taken to provide measurements of sufficient resolution and precision to allow extraction of the dec-cen signal at the earliest possible moment to make the most efficient use of the data. This consideration cannot be overlooked when designing joint monitoring sites geared toward weather and interannual and dec-cen studies.

In an analogous manner, the reliance of dec-cen studies on modeling demands considerable computing resources, since the models used in these efforts are often subject to long-term numerical drift in analyzing long timescales. This inadequacy simply reflects an inadequate treatment of the higher-order physics that often serve as the feedback mechanisms required to eliminate such drift. However, such higher-order physics typically involve more detailed regional or local-scale boundary interactions, which again require higher resolution, either in the vertical or horizontal dimension, or both. Over longer timescales the slower components of the system have an opportunity to become more intimately involved in climate evolution, so better treatment of additional components is also required. Further, the simulations themselves must involve much longer simulation times to resolve long timescales adequately. Obviously, the computer resources demanded by such models are extensive. Therefore, there must be a concerted effort to make the fastest computers readily available, so as to facilitate widespread access by a very broad and diverse modeling community. Sufficient resources are also needed so that the simulations required can be made as quickly and as often as needed.

Dec-cen climate studies are in their infancy, but advances and understanding are coming quickly. Because of the potential that climate change has to influence society dramatically over the timescale of a human life, we must make serious efforts to foster this research and build understanding to provide a sound scientific basis for national policy. Only then can policy makers take the necessary steps to ensure our long-term well-being—regardless of whether future climate changes are driven by natural or anthropogenic means.

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5

Changes in the Chemistry of the Atmosphere

SUMMARY

Within the atmospheric chemistry component of the U.S. Global Change Research Program there is a well-defined science focus with a track record of dealing with public policy implications. Development and implementation of the Montreal Protocol rested on a solid scientific foundation, realized through a strong international network of scientists and, within the United States, a multiagency effort led by the National Aeronautics and Space Administration (NASA). In fact, the model of an international, integrated, and periodically repeated assessment was largely formed from the United Nations Environment Programme/World Meteorological Organization Ozone Assessments. Moreover, this research area has a rich history of interaction with the human dimension components at fine spatial scales, as a natural consequence of air pollution studies and policies. Current developments in atmospheric chemistry are revealing the close links between chemistry, radiation, dynamics, and climate. Examples include the powerful role played by aerosol formation in both the boundary layer and the upper troposphere, chemical initiation of subvisible cirrus in the region of the tropopause, the control exerted by water vapor and temperature on the sharply nonlinear partitioning of halogen and hydrogen radicals in the lower stratosphere, and the importance of stratosphere-troposphere exchange on the composition and meteorology of the upper troposphere and lower stratosphere.

However, there are significant lessons to be remembered—lessons resulting from significant research shortcomings. Failure to recognize the Antarctic ozone hole sooner demonstrates the consequences of overreliance on models and how the selected observational strategies are so critically tied to success. This lesson

must not be forgotten in studying the complexities of climate, ecosystems, and the chemistry of the troposphere.

Today, we have far deeper knowledge about the chemistry of the atmosphere than we did just a decade ago. We also know more clearly what we do not know. These issues are also addressed in a recent National Research Council report (NRC, 1998) that is consistent with the perspective put forward in this chapter. Key challenges to atmospheric chemistry in the coming decade can be expressed in five Research Imperatives, where each Research Imperative combines one or more primary Scientific Questions with the need to know from a human dimensions perspective:

- *Stratospheric ozone and ultraviolet (UV) radiation.* Define and predict secular trends in the intensity of UV exposure that the Earth receives. Document the concentrations and distributions of stratospheric ozone and the key chemical species that control its catalytic destruction and elucidate the coupling between chemistry, dynamics, and radiation in the stratosphere and upper troposphere.
- *Greenhouse gases.* Determine the fluxes of greenhouse gases into and out of the Earth's systems and the mechanisms responsible for the exchange and distribution between and within those systems. Expand global detection techniques to elucidate the processes that control the abundances and variability of atmospheric CO_2, CH_4, N_2O, and upper-tropospheric/lower-stratospheric O_3 and water vapor.
- *Photochemical oxidants.* Develop the observational and computational tools and strategies that policy makers need to effectively manage ozone pollution, and elucidate the processes that control and the relationships that exist among ozone precursor species, tropospheric ozone, and the oxidizing capacity of the atmosphere.
- *Atmospheric aerosols and UV/visible radiation.* Document the chemical and physical properties of atmospheric aerosols, and elucidate the chemical and physical processes that determine the size, concentration, and chemical characteristics of atmospheric aerosols.
- *Toxics and nutrients.* Document the rates of chemical exchange between the atmosphere and ecosystems of critical economic and environmental import, and elucidate the extent to which interactions between the atmosphere and biosphere are influenced by changing concentrations and depositions of harmful and beneficial compounds.

INTRODUCTION

The chemistry of the Earth's atmosphere has emerged as a central theme in studies of global change. Atmospheric chemistry provides the scientific foundations to understand a number of phenomena that are part of global change. These phenomena include (1) changes in UV dosage at the Earth's surface owing to the intrinsically chemical nature of the catalytic loss of stratospheric ozone, (2) changes in the dynamics and radiative structure of the climate system through altered thermal forcing by ozone in the upper troposphere, (3) changes in the concentration of highly oxidizing species in urban as well as remote rural regions,[1] and (4) changes in the acid levels of depositions in a variety of ecosystems. In addition, work on the chemistry of the atmosphere provides hard examples of how the scientific method can succeed in guiding public policy.

What kind of research can successfully attack global-scale problems, problems that are intrinsically complex yet require reasonably unequivocal answers for international decision making and subsequent enforcement? Addressing this question is the objective of this chapter; the issue is attacked in four steps. First, case studies are presented that illustrate the successful execution of research in which hypotheses are tested by means of observations, leading to identification of cause and effect and thus to identification of the agent of change. This case study approach, while incomplete because of length limitations, helps address a fundamental question: *Why is it in the national interest that we have a global change research program to study the planet?* This question deserves careful consideration. Have we learned from scientific inquiry facts that constitute a decided reordering in our thinking about how the Earth functions? Have there been notable discoveries? Are there clear links between the discoveries associated with the national program and our economic competitiveness?

Second, we identify the key unanswered scientific questions that confront the field of atmospheric chemistry today. There are three categories of such questions:

1. What are the secular and episodic trends in concentrations of environmentally important atmospheric species, on local to global scales? What mechanisms control these concentration changes?
2. How are the concentrations of these species likely to change in the future? What are the most effective and feasible policy options for managing these changes?
3. What are the societal, economic, climatic, and environmental effects of present and future trends in the concentrations of these species?

Third, we review lessons learned over the past three decades that bear directly on research strategies for the future. These lessons range from general principles about posing and testing hypotheses regarding the Earth system to more detailed points about how specific observational strategies are selected to establish cause and effect.

Fourth, we address what is needed to successfully attack the major unanswered questions confronting the field, including theoretical approaches, observational strategies, instrument and platform development, and data handling and storage. We identify five primary research imperatives for atmospheric chemistry in global change research—the research imperatives presented in the opening paragraphs of this chapter. With these disciplinary imperatives come infrastructure initiatives, without which the research cannot be executed. Lessons extracted over the past four decades of research provide substantial guidance for such infrastructure initiatives.

CASE STUDIES

This section describes selected scientific cases that led to diagnoses central to studies of global change. In describing these developments attention is given to the ways that such transitions in our scientific thinking can be linked to specific public policy initiatives and to how such cases have been related to both environmental decisions and technological developments. Thus, we address the questions: *Why is it in the national interest to pursue this research? Are there links between this research and economic competitiveness?*

The Antarctic Ozone Hole

Discovery and diagnosis of the Antarctic Ozone Hole were a major surprise for both scientists and the public policy structure. In worldwide studies extending back to the 1950s, the amount of ozone over the Antarctic was tracked each year through its seasonal cycle. In the late 1970s an anomalous deficit was observed in total ozone amount in the late-winter observations. In 1985 the British Antarctic Survey reported for the first time in the scientific literature[2] that dramatic losses were occurring in the ozone concentration over Halley Bay and that the degree of ozone loss was worsening as the decade progressed. Theories about the cause of this unprecedented loss blossomed. Explanations ranged from simple redistribution by atmospheric motion to chemical reactions initiated by magnetic field focusing of solar electrons and protons. Such theories were put forward by serious scientific research groups in an international effort to diagnose the cause of this unexpected development.

A number of expeditions were planned to gather more complete information. In 1986 NASA planned an airborne expedition using the ER-2 aircraft to penetrate the region of the stratosphere where ozone was disappearing. The mission, executed in August and September 1987 from Punta Arenas, Chile, and supported by concurrent laboratory and modeling studies, demonstrated unequivocally that ozone was destroyed by chlorine and bromine radicals (see Figure 5.1). The role of chlorofluorocarbons (CFCs)—the molecules that transport chlorine to the stratosphere—in the destruction of ozone over the Antarctic rests on three discoveries from the NASA mission.[3] The first discovery was that the region of severe ozone depletion was isolated from the rest of the stratosphere by the polar night jet that defines the perimeter of the Antarctic vortex. This isolation creates a continental-scale "containment vessel," creating a sharp transition in the concentration of key chemical species associated with the destruction of ozone. The existence of this barrier preventing exchange is shown clearly by the high-resolution aircraft data in Figure 5.1. The second discovery from that mission linking CFCs to Antarctic ozone destruction is the documented evolution of the anticorrelation between O_3 and ClO occurring in the stratospheric containment vessel. As Figure 5.1 shows, the initial conditions established on 23 August, as sunlight returned to the region, demonstrate that O_3 had emerged from the polar night largely unaffected. Three weeks later, on 16 September, ozone had eroded sharply in the presence of high ClO concentrations in the containment vessel. The third confirming discovery emerged from laboratory studies supported by NASA that determined the rates of reactions responsible for destruction of ozone by chlorine and bromine radicals. These laboratory results allowed direct quantitative comparison of the two sets of aircraft observations: (1) observed concentrations of ClO and BrO in the containment vessel and (2) the rate of ozone disappearance in the containment vessel.

The case of Antarctic ozone depletion is particularly notable in the context of global change because of the severity of the phenomenon and the isolation afforded by the stratospheric containment vessel. The main elements of the scientific case linking CFC release to ozone destruction, as summarized here, have been extensively covered and critiqued in the international scientific literature. Taken together, the three major findings in the case provide irrefutable evidence that the dramatic reduction in stratospheric ozone over the Antarctic continent would not have occurred had CFCs not been synthesized and added to the atmosphere.

There have been additional surprises in the study of stratospheric ozone depletion as well. In 1989 and again in 1991 to 1992, NASA airborne missions staged from Stavanger, Norway, Fairbanks, Alaska, and Bangor, Maine, revealed that the containment vessel over the Arctic contained highly amplified concentrations of the same ClO radical discovered over the Antarctic.[4] Because ozone destruction requires high concentrations of chlorine radicals, sunlight, and time, ozone loss over the Arctic is less severe: the slightly higher temperatures over the Arctic allow the system to recover faster, by reducing the length of time that chlorine radicals remain at high concentrations in the containment vessel. In the past five years several northern hemisphere late-winter/early-spring seasons have been marked by dramatic reductions in column ozone at high latitudes.[5]

High-Speed Civil Transport and Ozone Loss

The United States is the world's leader in aircraft design and the development and sale of civilian commercial aircraft. NASA has developed a research program to establish the response of ozone to injections of combustion products (NO_x, H_2O, particulates) from the proposed High-Speed Civil Transport (HSCT).

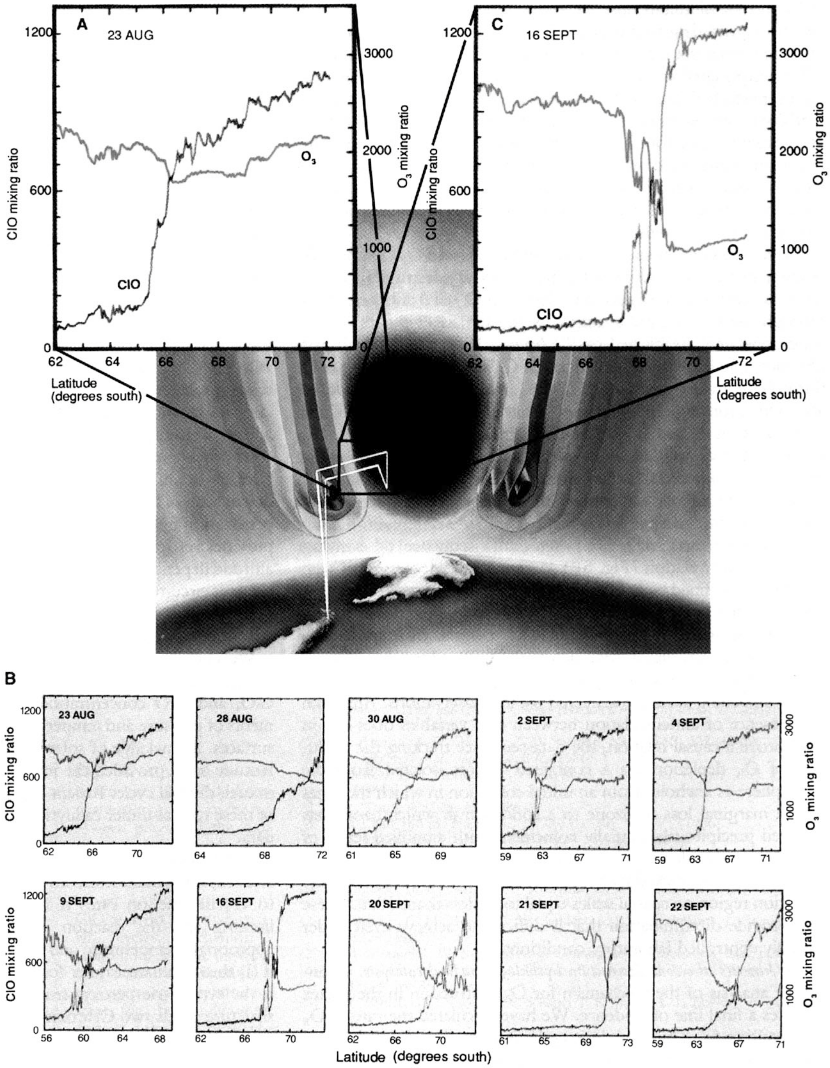

FIGURE 5.1 Rendering of the containment provided by the circumpolar jet that isolates the region of highly enhanced ClO over the Antarctic continent. Evolution of the anticorrelation between ClO and O_3 across the vortex transition is traced from (A) the initial condition observed on 23 August 1987 on the southbound leg of the flight; (B) summary of the sequence over the 10-flight series; and (C) imprint on O_3 resulting from three weeks of exposure to elevated levels of ClO. Data panels do not include dive segment of trajectory; ClO mixing ratios are in parts per trillion by volume; O_3 mixing ratios are in parts per billion by volume. SOURCE: Anderson et al. (1991). Courtesy of the American Association for the Advancement of Science.

The first direct experiments on the ER-2 aircraft recast our understanding of ozone loss in the lower stratosphere. Commercial aircraft sales represent an international market measured in tens of billions of dollars annually. Development of the HSCT is a main component in the international battle for leadership in this field. A key issue for this development is that the nitrogen oxide/particulate/water vapor effluent from the proposed aircraft could trigger both enhanced ozone loss in the stratosphere and radiative changes linked, through water vapor changes and cloud formation, to climate changes. Senate hearings in the early 1970s hinged significantly on the prospect of damage to the ozone layer by large fleets of supersonic transports resulting from NO_x emissions.[6] Equally important, however, is recognition that, if an aircraft is detrimental to global ozone and/or climate, business decisions to build such an aircraft are compromised.

NASA is carrying out a research effort with airborne missions[7] to test fundamental ideas about processes that control tropospheric and stratospheric ozone and, in particular, how the proposed HSCT and subsonic aircraft may alter those processes. The past three years have witnessed two important developments in our understanding of processes that control the catalytic destruction of ozone in the lower stratosphere. The first development emerged out of simultaneous NO_x/NO_y observations[8] during NASA's research and analysis airborne mission to the Arctic. The mission found that aerosols (minute liquid droplets) have a dramatic impact on the fraction of reactive nitrogen tied up in free radical form (NO and NO_2). These ER-2 in situ observations clearly demonstrated that NO_x was converted to NO_y, thereby providing a natural "sink" for any reactive nitrogen compound added to the lower stratosphere and, in particular, for the combustion effluent from the proposed Mach 2.4 HSCT. This result constitutes the first serious challenge to the two-decades-old premise that catalytic destruction of ozone in the lower stratosphere is dominated by nitrogen radicals (NO_x). It was this fundamental tenet—that ozone removal in the lower stratosphere is rate limited by NO_2—combined with the realization that a significant fleet of supersonic transports would add appreciably to the nitrogen oxide budget of the lower stratosphere, that impugned supersonic transports in the early 1970s.[9]

The second key development emerged from NASA's Stratospheric Photochemistry, Aerosol, and Dynamics Expedition of May 1993 and has subsequently been confirmed in more recent airborne missions. This ER-2 mission was the first to include a new generation of solid-state laser experiments capable of detecting OH and HO_2, thereby completing an ensemble of instruments capable of simultaneous in situ detection of each of the rate-limiting radicals in the dominant catalytic cycles (NO_2, ClO, BrO, and HO_2) and of the key coupling radicals NO and OH. These ER-2 observations[10] demonstrated the predominance of odd hydrogen HO_x) and halogen free radical (ClO_x and BrO_x) catalysis in determining the rate of removal of ozone in the lower stratosphere. A single catalytic cycle, rate limited by $HO_2 + O_3 \rightarrow HO + O_2 + O_2$, was found to account for nearly half the total O_3 removal in the midlatitude northern hemisphere lower stratosphere. Halogen radical chemistry was found to be responsible for 30 percent of the

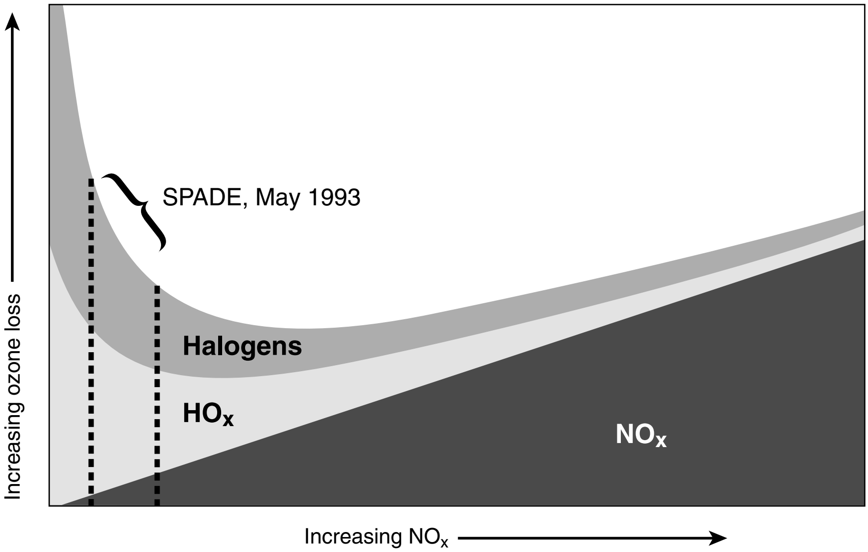

FIGURE 5.2 The O_3 removal rate is shown versus NO_x. Because of the coupling that exists between the radical families, the response of the total O_3 removal rate to changes in NO_x is highly nonlinear. At sufficiently low NO_x, such as observed during the NASA mission, the removal rates are inversely correlated with NO_x. SOURCE: Wennberg et al. (1994). Courtesy of the American Association for the Advancement of Science.

catalyzed loss of O_3, with reactions involving bromine sustaining half of the halogen catalytic cycles. Of critical importance to the HSCT, this NASA mission demonstrated that in the region sampled by the ER-2 the rate of catalytic ozone destruction is *inversely* correlated with total NO_x loading. The relationship between ozone loss rates and added NO_x is most clearly captured in a 1994 figure displayed in Figure 5.2.

These two developments changed decidedly the scientific community's judgment about the expected impact of the NO_x component of the HSCT effluent. Specifically, if there were a region of the stratosphere where addition of NO_x would actually *decrease* the rate of ozone catalytic destruction, it becomes plausible, contingent on the design of the aircraft and the dynamical and chemical characteristics of the stratosphere at higher altitudes, that addition of NO_x to the lower stratosphere could leave the ozone column virtually unaffected. These ER-2 results decidedly rearranged our thinking on lower-stratospheric ozone photochemistry.

There are, of course, a number of other key examples, including the diagnosis by Chameides et al. (1988) showing the coupled impact of volatile organics and NO_x on urban ozone production and the demonstration by Charlson et al.

(1995) of the importance to climate forcing of anthropogenic aerosols. There have also been key examples of direct sampling in supersonic aircraft exhaust in the stratosphere.[11]

A RESEARCH AGENDA FOR THE NEXT DECADE

The Scientific Questions facing atmospheric chemistry today are intellectually profound but also of vital social and economic importance. They relate to atmospheric constituents that are fundamentally important to our environment: stratospheric ozone, greenhouse gases, ozone and photochemical oxidants in the lower atmosphere, atmospheric aerosols or particulate matter, and toxics and nutrients. It is perhaps a measure of the strides made in recent decades that the issues of atmospheric chemistry are familiar now to the general public, policy makers, and scientists alike. Continued progress will require an ambitious and judicious commitment of financial, technological, and human resources to document the changing composition of the atmosphere and elucidate the causes and potential consequences of these changes.

Key Scientific Questions

The principal focus for atmospheric chemistry research will be on the environmentally important atmospheric species that, by virtue of their radiative and/ or chemical properties, affect climate, key ecosystems, and living organisms (including humans). From an intellectual point of view these species are interesting because they are central to the life support system of our planet. From a societal point of view they are of interest because they directly impact human health and welfare. Out of this focus emerges the challenge for atmospheric chemistry research in the coming decades: development and application of the tools and scientific infrastructure required to document and predict the concentrations and effects of environmentally important atmospheric species on local, regional, and global spatial scales and on daily to decadal timescales.

Stratospheric Ozone and UV Radiation Imperative

The stratosphere is a dynamical/radiative system[12] that exports ozone from the high-altitude tropics to mid/high latitudes along downward-sloping surfaces, defined by constant mixing ratios of tracers such as N_2O and CH_4. The coherence of these tracer surfaces as a vertical coordinate, revealed by tight regression relationships, is a dramatic and simplifying feature of the stratosphere.[13] Recognition of this fact has profound implications for research strategies in the next decade. Material enters the stratosphere primarily in the cold inner tropics in a process that desiccates the air, confines its point of entry, and establishes a “leaky chimney” that persists well into the middle stratosphere, dictating poleward motion from the tropics, as shown in Figure 5.3.

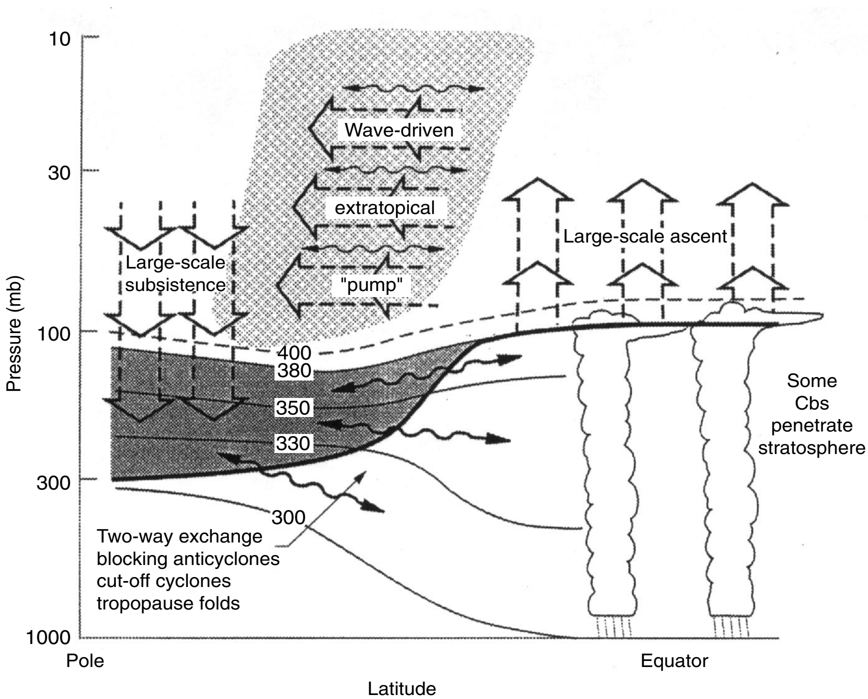

FIGURE 5.3 Dynamical aspects of stratosphere-troposphere exchange. The tropopause is shown by the thick line. Thin lines are isentropic or constant potential temperature surfaces (in degrees Kelvin). The heavily shaded region is "lowermost stratosphere," in which isentropic surfaces span the tropopause and isentropic exchange by tropopause folding occurs. The region above the 380 K surface is the "overworld," in which isentropes lie entirely in the stratosphere. Light shading in the overworld denotes wave-induced forcing (the extratropical "pump"). The wavy double-headed horizontal arrows denote meridional transport by eddy motions, which include tropical upper-tropospheric troughs and their cutoff cyclones, as well as their midlatitude counterparts, including folds. The broad vertical arrows show transport by the global-scale circulation, which consists of tropical upwelling and extratropical downwelling, driven nonlocally by the extratropical pump. This large-scale circulation is the primary contribution to exchange across isentropic surfaces (e.g., the ~400 K surface) that are entirely in the overworld.

Exchange between the extratropical boundary of the chimney and midlatitudes occurs on timescales of a very few months; this meridional exchange may be highly seasonally dependent. Transfer through the confines of the chimney is largely uncharacterized. Vertical exchange in the extratropics occurs via a sequence of equatorward-vertical-poleward motions. Polar regimes are characterized by rapid cooling in fall, with subsidence of many kilometers associated with the establishment of a strong polar jet that restricts exchange. This jet confines the winter polar stratosphere, most acutely in the southern hemisphere, and plays a significant role in the annual dynamical cycle of the stratosphere. The subtropical jet, the respective polar jets, and the tropopause constitute barriers to exchange; the low and high latitudes in each hemisphere are to a degree dynamically coupled in the lower stratosphere. Predicting accurately the path taken by material from a given point in the stratosphere in a given season is a central unanswered question. Our understanding of the response of the stratosphere to natural and inflicted changes is seriously compromised by this lack of understanding.

In formulating a strategy for studying the stratosphere, we have identified five basic scientific questions that we believe will motivate research on stratospheric ozone in the coming decades (see Box 5.1). The essential research activities that will be required to address these questions are outlined later in the section on research imperatives.

Atmospheric Greenhouse Gases Imperative

Observed increases in the concentrations of CO_2, CH_4, N_2O, and CFCs provide one of the clearest manifestations of global change in the atmosphere. Historical trends in H_2O and O_3 have yet to be quantitatively characterized. However, limited data suggest that tropospheric ozone concentrations may have

BOX 5.1 Stratospheric Ozone: Key Scientific Questions

1. Will evolution of the Antarctic stratospheric ozone "hole" proceed as expected, with a period of continued increasing intensity, followed by recovery to normal conditions? Will the Arctic emulate the Antarctic?
2. How will the midlatitude ozone depletion evolve? What mechanisms are controlling this erosion? How sensitive is this ozone erosion to temperature, water vapor partial pressure, sulfate/nitrate concentration, and aerosol loading and can we develop models to correctly simulate this evolution?
3. What is the role of the largely unexplored tropical region of the stratosphere in global ozone change?
4. What are the interactions between stratospheric ozone depletion and climate change?
5. What are the consequences of current and future perturbations, such as aircraft emissions and volcanic eruptions, on stratospheric ozone concentrations?

BOX 5.2 Greenhouse Gases: Key Scientific Questions

1. How do the natural carbon and nitrogen cycles control the amounts of CO_2, CH_4, and N_2O in the atmosphere and how are these cycles affected by human activities? More specifically:
   a. What are the regional sources and sinks of CO_2 other than fossil fuel burning?
   b. How large are the individual CH_4 sources?
   c. What are the missing sources of N_2O?
   d. What causes year-to-year changes in the trends of greenhouse gases?
2. How are CO_2 increases correlated with O_2 decreases as a function of altitude, latitude, longitude, and season?
3. Are the Montreal Protocol and successor agreements effective in mitigating the climatic warming from CFCs and HCFCs? Which new halogenated compounds may affect climate in the future?
4. What are the trends for O_3 in the troposphere and stratosphere and the causes?
5. In the upper troposphere, how are the formation of subvisible and visible cirrus—significant modulators of the escape of infrared radiation from the Earth system—affected by the presence of water vapor, sulfate, and nitrates?
6. What are the trends in water vapor in the upper troposphere and lower stratosphere and the causes?

increased by a factor of two or more in this century, while stratospheric ozone concentrations have decreased over the past 20 years. In addition, there are preliminary indications that stratospheric H_2O concentrations are currently on the rise.

The research strategy in the area of greenhouse gases is motivated by one central question: *What will be the concentrations of greenhouse gases in the next century?* Out of this main motivating question we have identified six critical scientific questions for investigation (see Box 5.2). These examples underscore yet again the mechanistic links between chemistry and the biosystem and between chemistry and issues of cloud/radiation feedback in the climate system.

The essential research activities that will be required to address these questions are outlined later. These activities are organized into three categories: (1) research related to the primary greenhouse gases that are emitted directly into the atmosphere; (2) research related to ozone, whose source is entirely photochemical; and (3) research activities related to H_2O, whose sources are both surface emissions and photochemical. In general, these research categories focus first on enhancements of successful strategies that are currently under way and then progress to new strategies requiring technological developments and, in many cases, the identification of new resources. Finally, it should be noted that many of these research activities are also relevant to other issues in atmospheric chemistry highlighted in this report. For example, investigations of the distributions and surface exchange rates of N_2O, CH_4, and the halogenated compounds, as well as O_3, are clearly of interest in the study of stratospheric ozone and photochemical oxidants.

Photochemical Oxidants Imperative

Elevated levels of oxidants on urban and regional scales in the industrialized countries of the world are proving to be among the most intractable of air quality problems.[14] To meet the information needs of society, the goals of atmospheric chemistry research in the next two decades must include more complete understanding of the processes determining the distribution and trends of photochemical oxidants and their precursors on urban, regional, and global scales. To achieve this understanding, four critical motivating scientific questions must be addressed in the coming decades (see Box 5.3).

BOX 5.3 Photochemical Oxidants: Key Scientific Questions

1. What determines the ability of the atmosphere to cleanse itself of pollutants, both now and in the coming decades? How important are multiphase reactions? More specifically:
   a. To what extent does our current understanding satisfactorily explain simultaneous measurements of OH concentrations and the principal OH chemical production and loss processes?
   b. Can the oxidation of compounds or the appearance of their oxidation products be successfully used to infer representative concentrations of OH, whether seasonally and regionally or annually and globally?
   c. To what extent do other oxidants (NO, H_2O_2, halogen atoms, etc.) play significant roles?
   d. To what extent do changes in stratospheric ozone, climate, and/or cloud cover affect the oxidizing capacity of the lower atmosphere?
2. What determines the distribution of ozone in the troposphere and how is it likely to change in the coming decades? More specifically:
   a. What fraction of tropospheric O_3 can be attributed to transport from the stratosphere and how does this change with meteorology and season?
   b. What portion of O_3 precursors are emitted from natural (biogenic) sources and how will these emissions change with natural perturbations (e.g., meteorological variability) and human-induced perturbations (e.g., land use, climate change)?
   c. What is the contribution of urban pollution to rural and regional O_3 and, conversely, what is the impact of rural and regional O_3 on urban pollution?

(continued)

BOX 5.3 Continued

d. How does meteorological variability affect the trends of O_3 and/or its precursors?
e. What are the major sources of nitrogen oxides in each region of the atmosphere over various geographic regions? What are the rates of NO_x emissions from these sources?
f. Which major reservoir and oxidizing species and which gas-phase and heterogeneous chemical processes are responsible for partitioning in the NO_y family?
g. Where and when is the production of O_3 limited by the availability of volatile organic compounds (VOCs) or NO_x? What are the sources and emission rates of VOCs?
h. What are the trends in regional and local O_3 precursors (NO_x, VOC, CO)?[15]

3. How can atmospheric models be improved to better represent current atmospheric oxidants and predict the atmosphere's response to future levels of pollutants? More specifically:
   a. What laboratory research is required to understand the fundamental chemical processes (heterogeneous and homogeneous) involved in tropospheric oxidant formation?
   b. What atmospheric measurements are required, and of what precision and accuracy, to evaluate and apply diagnostic and predictive models of tropospheric oxidant chemistry?
   c. What are the quantitative certainties associated with estimates from diagnostic and predictive models of tropospheric oxidant chemistry?
   d. How can models of tropospheric oxidant chemistry be improved to incorporate direct and indirect effects of multiple interacting forcing agents (such as climate change, stratospheric ozone depletion, and anthropogenic perturbations)?

4. How can we evaluate and improve our air quality management strategies for photochemical oxidants? More specifically:
   a. What design and implementation strategies will provide monitoring networks capable of determining whether control measures for photochemical oxidants are having the intended impact?
   b. What design and implementation strategies will yield monitoring networks capable of determining, for a particular air quality problem, what part of the problem is essentially irreducible (i.e., natural emissions of ozone precursors and stratospheric influx of ozone) and what part of the ozone problem is potentially controllable (i.e., human-made precursor emissions)?

To successfully address these questions, it must be recognized that photochemical oxidants research is truly data poor and measurement limited. Significant progress in this area will require a commitment to acquire high-quality observational data that are global in coverage but with high enough spatial and temporal resolution to reveal the important chemical and physical processes in the production, transport, and removal of photochemical oxidants. A research strategy that is both evolutionary and revolutionary will be required.

Atmospheric Aerosols and UV Radiation Imperative

Atmospheric aerosols have important impacts on human health, quality of life, and materials degradation. Another NRC (1992) report summarizes key aspects of this issue. Despite recent advances in appreciating the importance of atmospheric aerosols, our understanding of this critical class of atmospheric species is in its infancy. One notable reason for this failure is the complexity of aerosols. Compared to gases, aerosols have additional dimensions: an infinite number of sizes and a variable mixed composition. We are not able to fully comprehend the impacts of aerosols now, and we cannot make predictions about how the impacts will change in the future through human activities.

The important questions about atmospheric aerosols in the next decade concern their effects on climate, atmospheric chemistry, and human health and well-being (see Box 5.4). To answer these questions we must go far beyond our current state of knowledge of atmospheric aerosols. The essential elements of the research strategy that will be needed are outlined in the section on research imperatives later in this chapter. A more detailed discussion of many aspects of this strategy can be found in *A Plan for a Research Program in Aerosol Forcing and Climate* (NRC, 1992).

Toxics and Nutrients Imperative

Many of the atmosphere's naturally occurring components can have toxic and/or nutritive effects on the biosphere.[16] Myriad toxic and nutritive substances in the atmosphere are significantly influenced by anthropogenic activities. While

BOX 5.4 Atmospheric Aerosols: Key Scientific Questions

1. What is the role of natural and anthropogenic aerosols in climate and how might future changes in levels of aerosol precursors affect this role?
2. How are natural and anthropogenic aerosols likely to affect stratospheric and tropospheric ozone and the cleansing capacity of the atmosphere in the future? What are the sources and emission rates of natural aerosols?
3. What is the role of atmospheric chemistry in changing the composition of aerosols that affect human health, the environment, visibility, and infrastructure materials?

BOX 5.5 Toxics and Nutrients: Key Scientific Questions

1. How are interactions between the atmosphere and biosphere influenced by changing atmospheric concentrations and by the deposition of harmful and beneficial compounds?
2. More specifically, from the viewpoint of atmospheric chemistry, what are the rates at which biologically important atmospheric trace species are transferred from the atmosphere to terrestrial and marine ecosystems through dry and wet deposition?

we are beginning to identify the more acute cases of atmospheric toxicity, such as benzene, vinyl chloride, PCBs, and chloroform, and overfertilization for key ecosystems, our understanding is far too limited to assess the present extent of these problems or to predict future ones.

The essential elements of a research strategy to address these questions (see Box 5.5) are outlined in the section on research imperatives. The hard lessons that have been learned over the past few decades are discussed in the next section. These lessons must be kept in mind when the research strategy is discussed.

LESSONS LEARNED

The lessons that emerged from the last four decades of the twentieth century hold the key to fundamental progress. Only by considering this experience can an effective strategy be designed to characterize the processes underlying the ozone/climate system response to secular trends in chemical constituents, so that defensible predictions are possible. This section details both general research lessons and specific scientific lessons that should be applied.

Perhaps the most critical lesson is the realization that the stratosphere is severely undersampled, particularly from a mechanistic point of view. The Antarctic ozone hole emerged virtually unnoticed, although the removal of a major fraction of total ozone subsumed a significant fraction of our southern hemisphere. For more than two decades, from the early 1970s until the mid-1990s, nitrogen radicals were believed to dominate the destruction rate of ozone in the lower stratosphere of the Earth—a premise shown to be wrong in 1994. The central role of aerosols in the control of free stratospheric radical partitioning went unnoticed until 1992. Aerosols now constitute a dominant uncertainty in the *response* of the stratosphere to high-altitude aircraft, halogen emissions, volcanic eruptions, and other phenomena. While we know that ozone is eroding at midlatitudes at a rate that exceeds prediction, currently we can only speculate about the cause. Speculation does not lead to effective public policy.

It is important to carefully distinguish between observations designed to determine long-term trends in key variables and observations designed to test specific hypotheses defining the mechanism or process that controls the system. Both are critically important to scientific progress, but they have, in a vast number of key cases, very different experimental requirements.

The character, availability, and cost of observational platforms together have been the key link between global change research and the nation's intellectual resources, related technical and scientific developments, educational opportunities, and the execution of effective public policy initiatives. For many pivotal questions the appropriate platform may be a small fast-response satellite. For others the platform must be able to pass *through* the atmosphere on a carefully prescribed trajectory that orthogonally traverses the meteorological fields (velocity, potential vorticity, potential temperature, etc.). The platform must be robust enough to meet takeoff and landing constraints. The integration of instruments with the platform must be straightforward. The platform must be easily deployable to remote locations. It must also be capable of reaching the required altitudes with adequate duration and payload capabilities to address the essential questions.

The verification of models by "spot checking" is another approach that can be useful, though it has limitations in effectively linking chemical and dynamical processes and dynamical and radiative processes. Models must be continuously tested, and innovative new approaches linking observations and models must be developed.

Fundamental but incorrect tenets of the field can survive for decades in the face of many observations.

The degradation of spatial resolution, poor signal-to-noise ratios, the missing of key species in a selected array of simultaneous observations, and the inability to access latitudes, altitudes, solar zenith angles, and seasons are problems that profoundly cripple datasets. The heart of this lesson is remembering the distinction between gathering data, on the one hand, and clearly answering specific questions on the other.

The large variability within and between datasets is an enemy of unambiguous interpretation *unless* the proper complement of observations is obtained simultaneously; then variability becomes a powerful ally for the establishment of cause and effect.

Good public policy emerges from unequivocal scientific results. Again, speculation is not an adequate foundation for public policy.

In addition to these more general lessons, we have learned several more specific and critical scientific lessons, which have emerged from major scientific transitions in the study of the chemistry of the atmosphere (see Box 5.6).

BOX 5.6 Key Science Lessons Learned

1. Sharp gradients within the atmosphere are important to exploit, including polar jets, subtropical jets, the tropopause, and within the boundary layer.

2. Carefully selected simultaneous in situ observations with high spatial resolution are uniquely powerful in establishing specific cause and effect relationships in the atmosphere.

3. Long-lived chemical tracers provide the best "vertical coordinate" in the stratosphere to establish the regression relationships among variables in the atmosphere, thereby providing the basis for unambiguous linking of variables.

4. Dynamic range in the independent variables and the ability to hold all variables but one approximately constant are essential for obtaining key partial derivatives. These partial derivatives constitute the "response functions" of the system.

5. There exists a close relationship between the extraction of clear conclusions from a mission and the spatial and temporal coverage of an in situ measurement ensemble. In particular, the vertical axis in the measurement coordinate system in the stratosphere must be determined by high spatial resolution, simultaneous observations of long-lived tracers, as previously noted. A second aspect of this issue is the importance of diurnal observations for sorting out photochemical mechanisms. Finally, a third aspect is the importance of combining simultaneous highly accurate observations, taken at different seasons, to reveal fundamental changes in the transport rates of the atmosphere.

6. The altitude dependence of the regression relationships between photochemically active species (e.g., ozone) and the tracers (e.g., N_2O, CFC-11) must be defined as a function of season and latitude to significantly higher altitudes than the region of the stratosphere that must be quantitatively analyzed. The reason is that, over large regions of the lower stratosphere, diabatic descent brings stratospheric air down from altitudes well above current in situ platform capabilities (~20 km).

7. The dynamical context of a mission's deployment, established by accurate real-time modeling of temperature, pressure, potential temperature, and potential vorticity fields, together with accurate trajectory analyses, is essential both to daily deployment tactics and subsequent data analysis.

8. The incorporation of carefully selected new measurements in the ensemble of observations has unfailingly led to fundamental and unexpected transitions in our understanding of how chemical and dynamical mechanisms operate in the stratosphere.

RESEARCH IMPERATIVES: PRIORITIES FOR OBSERVATIONS, MODELING, AND THEORY

We turn next to the question of defining a research strategy that addresses the primary Research Imperatives:

- *Stratospheric ozone and UV radiation.* Define and predict secular trends in the intensity of UV exposure that the Earth receives. Document the concentrations and distributions of stratospheric ozone and the key chemical species that control its catalytic destruction and elucidate the coupling between chemistry, dynamics, and radiation in the stratosphere and upper troposphere.
- *Greenhouse gases.* Determine the fluxes of greenhouse gases into and out of the Earth's systems and the mechanisms responsible for the exchange and distribution between and within those systems. Expand global detection techniques to elucidate the processes that control the abundances and variability of atmospheric CO_2, CH_4, N_2O, and upper-tropospheric/lower-stratospheric O_3 and water vapor.
- *Photochemical oxidants.* Develop the observational and computational tools and strategies that policy makers need to effectively manage ozone pollution and elucidate the processes that control and the relationships that exist among ozone precursor species, tropospheric ozone, and the oxidizing capacity of the atmosphere.
- *Atmospheric aerosols and UV/visible radiation.* Document the chemical and physical properties of atmospheric aerosols and elucidate the chemical and physical processes that determine the size, concentration, and chemical characteristics of atmospheric aerosols.
- *Toxics and nutrients.* Document the rates of chemical exchange between the atmosphere and ecosystems of critical economic and environmental import and elucidate the extent to which interactions between the atmosphere and biosphere are influenced by changing concentrations and depositions of harmful and beneficial compounds.

The research strategy recommended here addresses such questions and hypotheses, which have been selected in view of their intrinsic scientific merit, particularly regarding the Earth's ability to sustain life. The recommended research strategy is also based on a plan of attack that relies on a flexible array of experimental and theoretical analyses. The objective is to test the most important questions expeditiously and efficiently. The selected manifold of state-of-the-art techniques reflects the use of new technical developments and diagnostic calculation methods, along with recognition of the distinction between establishing secular trends and determining the fundamental processes responsible for global-scale changes. Again, the research strategy also takes careful account of critical lessons from past scientific work.

Stratospheric Ozone and UV Radiation

Ultraviolet radiation reaching the Earth's surface is controlled first and foremost by the total overburden of ozone in the Earth's stratosphere and modified by aerosol loading in the lower troposphere. Our focus is thus primarily on ozone in the stratosphere, but we will also consider the question of aerosols in the final subsection covering this imperative. To begin, we examine secular trends in stratospheric ozone. This discussion underlines the critical role of stable long-term analyses of the altitude, latitude, longitude, and seasonal variations in ozone mixing ratios in the stratosphere. It also underlines the complementary but differing character of scientific analyses of secular trends in contrast to diagnoses of mechanisms. The latter mechanisms determine the chemical and physical changes that occur at all timescales on the global scale and are the focus of the second section. The third subject of discussion is the importance of tracers that establish the coordinate system within which all observations are interpreted. Finally, the principal contributions of fundamental laboratory studies are analyzed in the context of predicting changes in ultraviolet exposure of the Earth's surface.

Critical considerations in measuring stratospheric ozone depletion include the uninterrupted observation of total ozone, the altitude dependence of ozone changes, and the geographic and seasonal patterns of those changes, as determined with high temporal resolution and accuracy, using a combination of intercalibrated instruments on space-based and ground-based systems as well as airborne platforms. The fundamental nature of these research needs cannot be overemphasized in light of the problematic recent time gaps in our capability to monitor stratospheric ozone distributions from space.

Continuous cross-calibrated measurements of stratospheric ozone will document the extent of ozone loss and degree of ozone recovery if stratospheric halogen concentrations, water vapor, temperature, and other critical factors return to normal. These measurements will thus provide an essential gauge of the sufficiency of and/or world compliance with the international treaties devised to reverse the ozone depletion of the 1980s and 1990s.

Equally important, continuous measurements of stratospheric ozone will provide rapid warning of any unanticipated changes in the concentration and distribution of stratospheric ozone. The relationships between stratospheric ozone and various agents of chemical change are very complex and still poorly understood. As stratospheric chemical composition evolves under changing halogen loadings, the effects of perturbations—both natural and industrial—may vary unexpectedly. For example, we now know that volcanic eruptions into a chlorine-rich stratosphere can have a profoundly different effect on stratospheric ozone than they most likely had in the pre-CFC era. Similar phenomena may very well occur with other perturbations, such as those arising from aircraft emissions.

This analysis of secular trends has several key components. The first is the high accuracy analysis of long baseline trends in ozone total column measurements with spatial and temporal resolution. This tracking of decade to multidecade trends is a scientifically feasible goal, but it is not a pedestrian venture. It is also not an objective that can be attained without critical cross-checks from multiple independent techniques. The second component of analysis of secular trends is the need for high-accuracy analysis of the altitude dependence of stratospheric ozone changes. This problem is potentially much more intricate than the observation of total column ozone because of the need for high spatial resolution in the vertical, the need to tie observations to long-lived tracers, and the complications introduced by the injection of aerosols through volcanic eruptions.

Predicting Future Changes in UV Dosage: Establishing Cause and Effect in the Photochemical Cycles that Control Ozone Loss Rates

Accurately determining secular trends in the distribution of stratospheric ozone represents an essential arm of stratospheric ozone research in the coming decades. The need to understand potential changes in stratospheric chemistry in the face of changing sulfur, chlorine, bromine, N_2O, methane, CO_2, H_2O, and other chemical loadings requires understanding the underlying mechanisms. This understanding in turn depends on mapping the distribution and variability of the species that determine the magnitude of ozone depletion and establishing a clear definition of the chemical reaction network that links these species. The total rate of stratospheric ozone destruction is governed by numerous catalytic destruction cycles, whose rates are limited by the abundances of specific free radical species, such as OH, HO_2, ClO, BrO, and NO_2, as well as atomic oxygen. A question fundamental to the scientific understanding of ozone depletion is: What rate-limiting steps actually dominate ozone loss as a function of altitude, latitude, and season? Of equal importance: How do the rates and relative roles of each of these loss processes change as hydrogen-, chlorine-, bromine-, and nitrogen-containing species are added to or removed from the stratosphere and with superimposed changes in reactive surface area of aerosols, water, and temperature?

Clearly, the answers to these questions require mapping the relevant radical concentrations from the troposphere to altitudes subsuming most of the ozone column. The case studies earlier in this chapter demonstrate this point. However, to define more fully the future stratospheric ozone responses to perturbations we know are in progress (e.g., sulfur from volcanic injections, NO_x, aerosols and water from subsonic and supersonic aircraft, temperature changes triggered by decreases in ozone and increases in CO_2 and H_2O in the lower stratosphere, emissions of bromine and chlorine compounds), it is essential that we map the *partial derivatives* of the rate-limiting steps with respect to the variables on which the concentration depends, as well as the radical concentrations themselves. Figure 5.4 schematically illustrates the diagnostic power of this dual approach. In this case the loss rate of ozone from the catalytic cycles driven by

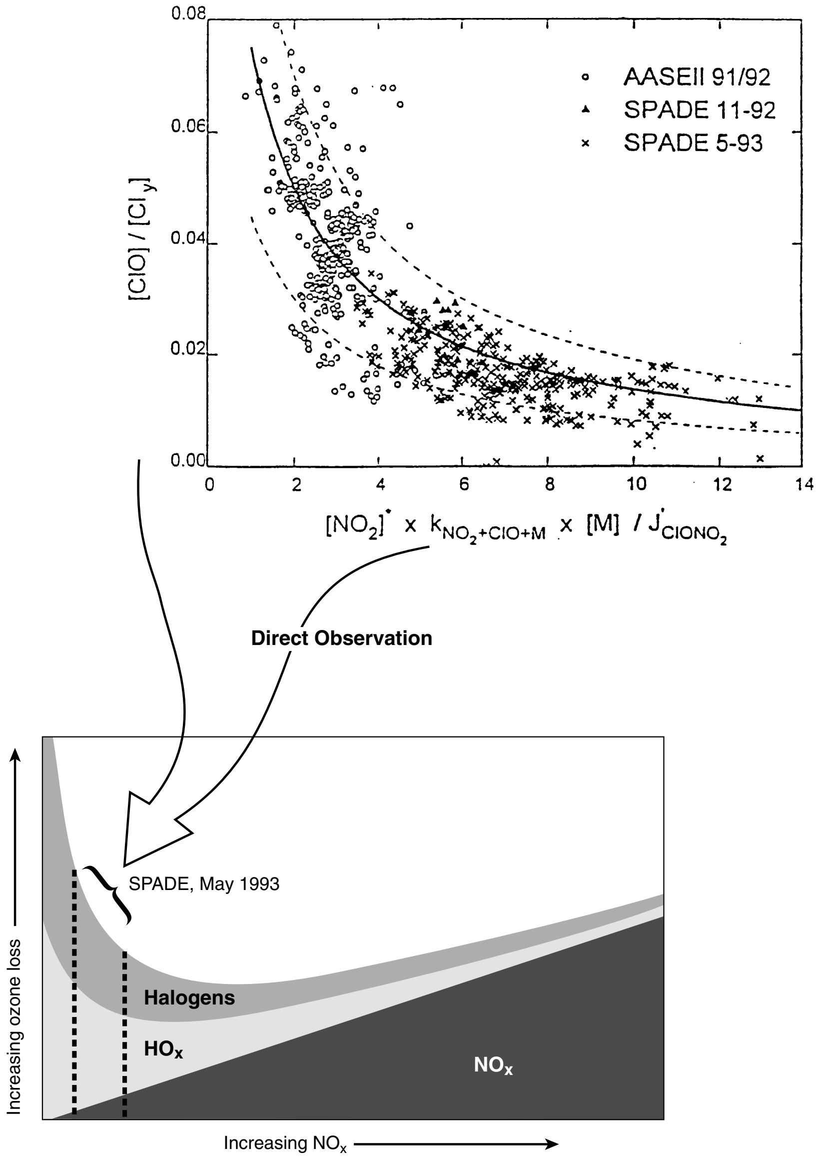

FIGURE 5.4 Schematic illustration of ozone loss rate as a function of NO_x concentration. Because of the coupling that exists between the radical families, the response of the total ozone loss rate to changes in NO_x is nonlinear. For example, at low NO_x concentrations, ozone loss rate was found to be inversely correlated with NO_x. Also shown are actual data obtained by the NASA ER-2 in the stratosphere, demonstrating that the specific slope of ozone loss is directly observable. SOURCE: Adapted from Wennberg et al. (1994). Courtesy of the American Association for the Advancement of Science.

HO_x, halogen, and NO_x radicals is illustrated as a function of NO_x concentrations (from high-altitude aircraft or from radical repartitioning resulting from volcanic eruption), with the total ozone loss given by the sum of the individual contributions. Because of the couplings that exist between NO_x and the other radical families, the response of ozone loss to a change in NO_x concentrations turns out to be a complex function that depends on the individual gradients in each of the rate-limiting steps with respect to NO_x. Because of the nature of these gradients, the total ozone loss is smallest at an intermediate NO_x concentration. Similar effects undoubtedly are seen in the dependence of ozone destruction cycles on other radical species. The point here is that the *response* of stratospheric ozone to various changes is measured directly by these partial derivatives. Partial derivatives are *observables* of the system, and thus identification of this pattern is a significant breakthrough that redefines the relationship between measurements and models.

In general, because the interdependence of concentrations of chemical species that control ozone loss changes over various spatial and temporal scales, measurements of these species must extend to the full range of relevant conditions. Doing so will require the simultaneous deployment of critical instruments, development of new instruments, development and deployment of new measurement platforms that can cover relevant stratospheric regions, and measurements of the variations of each of the rate-limiting radicals (and its catalytic ozone loss rate) relative to each of the other critical species. In particular, current altitude limitations for piloted aircraft that are subsonic, and thus acceptable for in situ observations, are 20 km. The heart of the ozone layer, however, extends above these altitudes by a scale height. Since the required observations of the linking reactions, via the partial derivatives, demand simultaneous observations of tracers (N_2O, CH_4, CO_2, SF_6), reservoir species (HCl, $ClONO_2$, H_2O, $BrONO_2$, $HONO_2$), and radicals (ClO, BrO, OH, HO_2, NO, NO_2, $O(^3P)$), these observations must be extended to altitudes of 25 km. Experience has shown that the required spatial resolution for these simultaneous observations must be equal to or better than 0.1 km. These requirements demand in situ observations of these species.

Predicting Future Changes in UV Dosage: The Coupling of Chemistry, Dynamics, and Radiation

The stratosphere is a coupled photochemical, dynamical, and radiative system in which ozone is exported from the high-altitude tropics to mid- and high latitudes along surfaces formed by constant mixing ratios of tracers such as N_2O and CH_4. The coherence of these tracer surfaces as a vertical coordinate is revealed by the tight correlations between these long-lived species and other reactive species. This regularity is both a dramatic and a simplifying feature that has led to important insights about the dynamics of the stratosphere and its role in defining the response of stratospheric ozone to chemical and physical perturbations. Air primarily enters the stratosphere in the cold inner tropics through a process that desiccates the air and confines the upwelling flow to the middle stratosphere, as shown in Figure 5.3.

The subsequent exchange of air between this upward-moving tropical air mass and stratospheric midlatitudes apparently occurs on timescales of a few months and varies by season. However, this exchange is largely uncharacterized and is a potential source of large uncertainty in our ability to predict the response of the stratosphere to perturbations. Polar regimes are characterized by rapid cooling in the fall, with subsidence of many kilometers associated with the establishment of a strong polar jet. This action, in turn, restricts mixing with the midlatitudes, thus isolating the winter polar stratosphere from the rest of the stratosphere during the winter months, especially in the southern hemisphere. The restriction of exchange with the wintertime polar stratosphere plays a significant role in the annual dynamical cycle of the stratosphere and is an essential element in the formation of large regions of severe ozone loss over the polar regions.

Diagnosing the mechanisms that control patterns of exchange between the stratosphere and troposphere, the tropical and extratropical stratosphere, and the polar stratosphere is a prerequisite for quantifying the mechanisms for polar and midlatitude ozone loss. This circumstance gives rise to another critical research activity—to elucidate the coupling of chemistry, dynamics, and radiation in the stratosphere. Because of the tight relationships between air mass origin and tracer concentrations, clarification can best be accomplished with spatially resolved (0.1 km), highly accurate, in situ observations of N_2O, CH_4, SF_6, CO_2, CFC-11, CFC-12, O_3, and NO_y, and determination of the age of the air mass in which the measurements are made. Such measurements can be carried out using instruments based on the ground, piloted aircraft, and robotic aircraft and small satellites. Additionally, trajectory and three-dimensional models are required to interpret these observations and, in the process, to improve the models themselves.

Because of the sharp concentration gradients, study of the region from the upper troposphere to 30 km must rely heavily on in situ observations. At higher altitudes, where vertical and horizontal gradients begin to soften, small satellites will be critical. The altitude overlap of these two observational strategies must be enhanced, for it is essential to obtain these coupled observation sets with seasonal (~1 month) frequency for a number of annual cycles.

Predicting Future Changes in UV Dosage: Characterizing the Chemical Processes that Control Gas-Phase and Heterogeneous Reactions

Predicting changes in stratospheric ozone requires knowledge in a number of chemical physics research areas—areas of research in which we now lack sufficient understanding to predict stratospheric ozone and thus UV dosage. Understanding radical-molecule reactivity at the molecular level is essential; defining the temperature and pressure dependence of the homogeneous gas-phase catalytic processes lies at the foundation of our understanding. It is also essential to understand the oxidation processes that carry reduced sulfur through to sulfuric acid, both in the open atmosphere and in the plumes from commercial aircraft. We must establish mechanistic insight into the processes that govern reaction pathways in the oxidation of organic species in the troposphere—particularly the lifetime and final product structures resulting from that oxidation sequence. We must develop molecular knowledge of which ternary sulfate, nitrate, and water mixtures form and grow particles in the atmosphere and of how this growth occurs at low temperatures and at the phase transition point, leading to frozen particles in the polar region and tropical tropopause regions.

Chemical transformations in the gas phase, or on or within condensed matter, that take place in the stratosphere ultimately determine the current and future composition of this region. The quantification and characterization of these processes through laboratory experiments (and in some cases computational techniques) provide the essential building blocks for interpreting, simulating, and predicting concentrations and changes in the stratosphere. Continued development and application of laboratory experiments and computational techniques to the study of stratospheric chemical processes are thus important components of any research strategy for the stratosphere. Especially critical in the coming decades will be investigation of heterogeneous processes, where our understanding lags far behind our knowledge of gas-phase homogeneous reactions.

Greenhouse Gases

Infrared active species absorb radiation from the Earth's surface and lower atmosphere and redirect part of this radiation back to the surface, increasing sea surface and land mass temperatures through the so-called greenhouse effect. Analysis of climate changes in response to secular trends in infrared species requires accurate knowledge of how the major infrared-active gases evolve over time and of the processes controlling the production and removal rates for those species in the atmosphere. These species include the primary infrared active molecules emitted directly into the stratosphere (e.g., CO_2, CH_4, N_2O, CFCs) and secondary greenhouse gases produced in the atmosphere by photochemical processes (e.g., O_3). Water vapor (H_2O), the most important of the greenhouse gases, is unique in that it is both emitted into the atmosphere (via evapotranspiration) and produced photochemically in the stratosphere from the oxidation of CH_4. Ozone is also unique in acting as both a greenhouse gas (by absorbing infrared radiation) and an important absorber of solar ultraviolet and visible radiation, as discussed earlier in the context of the stratospheric ozone and UV radiation research imperative.

Observed increases in concentrations of CO_2, CH_4, N_2O, and CFCs provide one of the clearest manifestations of global change in the atmosphere. Historical trends in H_2O and O_3 have yet to be quantitatively characterized. However, limited data suggest that tropospheric ozone concentrations may have increased by a factor of two or more in this century, while stratospheric ozone concentrations have decreased over the past 20 years. In addition, there are preliminary indications that stratospheric H_2O concentrations are currently on the rise.

For the most part the changing concentrations in atmospheric greenhouse gases appear to be driven by human activities, in the forms of energy use, industrialization, land use changes, and agriculture. Increases result from both changes in world population and changes in use patterns as economic development expands. The fact that these drivers of global change are not likely to abate in the coming decades without significant political and economic intervention has given the scientific debate over infrared active species and their climatic impact a sense of urgency and intensity. Moreover, while significant advances in our understanding of the sources and sinks of greenhouse gases have been attained in recent years, we are far from having a reliable predictive capability for the future evolution of their concentrations. Thus, not only our ability to predict future climatic trends but also our ability to formulate effective policy options to mitigate or adapt to future climatic changes remain highly limited.

The basic research strategy for studying atmospheric greenhouse gases is motivated by one pivotal question: What will the greenhouse gas concentrations be through the course of the next century? Arising from this central concern, we have identified six critical scientific questions for investigation (see Box 5.7).

The research initiatives required to address these questions are both extensive and essential, but they can be classified into three basic categories: (1) research related to the primary infrared active species emitted directly into the atmosphere (as well as linked observations that distinguish sources such as the CO_2-O_2 linkage); (2) research related to ozone, whose source is entirely photochemical but whose distribution is strongly affected by atmospheric motion; and (3) research objectives related to H_2O, whose sources are both surface emissions and photochemical.

In general, recommended research steps focus first on enhancements of successful strategies and then on new strategies that will require technological developments. Note that the research described here is directly relevant to other central issues in atmospheric chemistry identified in this report. For example, investigations of the distributions and surface exchange rates of N_2O, CH_4, and the halogenated compounds, as well as O_3, are clearly relevant to the study of ultraviolet exposure and photochemical oxidants.

Primary Infrared Active Species

The primary greenhouse gases can be roughly divided into two categories: the biogenic species whose sources and sinks are closely linked to biospheric processes (i.e., CO_2, CH_4, N_2O) and halogenated compounds (i.e., CFCs, HCFCs, SF_6). For the most part, halogenated compounds come from industrial activities,

BOX 5.7 Critical Scientific Questions for Greenhouse Gases Research

1. How do the carbon and nitrogen cycles control the amounts of CO_2, CH_4, and N_2O in the atmosphere? How are these cycles affected by human activities?
   a. What are the regional sources and sinks of CO_2, including the oceanic component, other than fossil fuel burning? How do changes in temperature affect these sources and sinks?
   b. How large are the individual CH_4 sources? How does the source strength depend on season? What is the temperature dependence of these sources?
   c. What are the missing sources of N_2O? How do agricultural practices affect N_2O fluxes?
   d. What causes year-to-year changes in the trends of the infrared active species?
2. Combustion of fossil fuel and organic material produces CO_2 and consumes O_2. How are the CO_2 increases correlated with O_2 decreases as a function of altitude, latitude, longitude, and season?
3. Are the Montreal Protocol and successor agreements effective in mitigating the climatic warming from CFCs and HCFCs? Which new halogenated compounds may affect climate in the future?
4 In the upper troposphere, how is the formation of subvisible and visible cirrus—significant modulators of the escape of infrared radiation from the Earth system—affected by the presence of water vapor, sulfate, and nitrates? What reactions are catalyzed on these frozen particles?
5. What are the trends in O_3 in the troposphere and stratosphere and what are their causes?
6. By what mechanism is water delivered to and distributed in the mid- to upper troposphere? What are the trends in water vapor in the upper troposphere and lower stratosphere?

providing a clear distinction between these compounds and biogenic greenhouse gases. However, there are notable exceptions: halogenated compounds such as CH_3Cl and CH_3Br have important interactions with the biosphere and thus fall into both categories.

Maintaining Current Concentration Monitoring Networks

The most robust large-scale signature of the sources and sinks of greenhouse gases and their time dependence will be variations in the mixing ratios of CO_2, CH_4, and N_2O and in their isotopic ratios. It is therefore essential that the current global monitoring networks for these parameters be maintained. For these data to be useful, high accuracy and precision will be required because the pertinent geochemical information is derived from small spatial and temporal variations.

In principle, estimates of the continental source of a "long-lived" trace gas can be obtained from measurements at a surface site that is subject to intermittent pollution events from a nearby continent.[17] For example, a pollution event on the west coast of Ireland is readily identified from trace gas concentration data; it appears as a temporal enhancement in the local concentration of a long-lived gas of industrial origin. Ratios of emissions of various halocarbons and N_2O to $CFCl_3$ were obtained from the covariance between each species and $CFCl_3$ using this approach.[18] If the magnitude of emissions of a reference gas is known and the sources are colocated, absolute source strengths of the other gases can be derived. Moreover, with a three-dimensional model that can reproduce synoptic scale pollution events, it should be possible to obtain perspective on the continental source strength of a gas without scaling to a reference gas.[19]

Thus, it appears that implementing a monitoring network to document changing greenhouse gas concentrations downwind of major source regions would provide critical data on the source strengths of these regions. Such information would prove highly valuable for constraining atmospheric budgets for these gases and could ultimately represent a means of verifying compliance with potential future international emissions agreements. However, the problem of defining the source strength for biogenic greenhouse gases using this method is somewhat more challenging than for CFCs, whose emissions are essentially constant through the year. Because the sources of biogenic gases vary with season, their background concentrations also vary seasonally. Thus, continuous measurements at both upwind and downwind sites will be required. The challenge will be to develop algorithms that can reliably unravel this information in a quantitative manner to define the background concentration and the excess over background caused by advection and pollutants from a given source region. An atmospheric transport model based on observed winds would play a key part in analyzing the data.

Developing a Systematic Method for Multiyear Flux Measurements and Vertical Profile Measurements over Continents

A predictive capability for infrared active species requires understanding how the surface exchange rates of these gases behave as a function of such factors as season, rainfall, and local, regional, and global climate variations. For the biogenic greenhouse gases this knowledge will require surface flux measurements, in concert with hydrological and climatic observations, over a variety of biomes and climate regimes over a multiyear period.[20] These measurements will prove critical in establishing empirical relationships between climatic conditions and biospheric emission and uptakes rates, as well as the biological mechanisms responsible for these relationships.

Vertical profiles over the continents, over horizontal scales of 2,000 to 3,000 km, will be required to infer the relevant flux information for the biogenic greenhouse gases. In addition, measurements from land surface sites are often difficult to interpret because of the effects of local sources and sinks. A critical advantage of profiles is that there is less sensitivity to details of vertical mixing. Profile sampling should be carried out throughout the year and at sufficient spatial density. The spatial scale is suggested by the current distribution of ecosystems and the spatial extent of major climate "anomalies," such as the 1988 drought in the United States. For the North American continent, this would probably be several dozen sites. Consideration of the expected signal-to-noise ratio suggests that a feasible and economical strategy for the near future would be the collection of automated flask air samples aboard light aircraft at twice-weekly intervals.[21] An advantage of such a system is that the samples could be analyzed for multiple species and isotopic ratios with tightly controlled calibration. Seasonal, and perhaps monthly, mass fluxes over the continent could be determined from such a system and related to variations in climate and analyzed in the context of three-dimensional climate and chemical transport models.

While multiyear flux measurements provide insight into the mechanisms responsible for gas exchange on scales of a few hundred kilometers, larger-scale studies are needed to establish the methodology and the validity of extrapolating this flux information to regional and global scales. This type of study, such as that planned for Brazil in 1998, represents a natural progression from the mesoscale studies carried out in the 1980s and early 1990s (e.g., the ABLE campaigns). It will require at least two years of ground experiments, two major aircraft campaigns, and a significant meteorology and transport modeling effort. These experiments would be greatly enhanced by the availability of advanced flux measurement technology and improved instrumentation. To address the global-scale flux/profile issue effectively, efficient use of robotic aircraft may be needed because of the combined requirement of simultaneous observations at high spatial resolution and the need for global and seasonal coverage.

Establishing a Consistent Approach to Measure the Flux of Infrared Active Molecules on the Global Scale in Remote Regions

The oceanic flux of the biogenic infrared active molecules represents a very important component of the atmospheric global budgets for these gases. Research must adequately characterize the process of air-sea gas exchange. Unfortunately, most air-sea exchange rates are not known to better than a factor of two and in some cases an order of magnitude. Direct measurements of fluxes over the oceans have not yet been successful in reducing this uncertainty because of shortcomings in current platforms and instrumentation. In principle, conventional eddy correlation methods can provide data of sufficient accuracy and precision, but this approach requires fast-response, highly precise velocity and species detection methods. For the long-lived trace gases the problem is compounded by the fact that the concentration gradients between atmosphere and ocean that must be measured are a very small fraction of the total concentrations, and, as a result, the measured differences are often masked by much larger effects caused by the fluxes of water vapor and heat. This problem must be addressed by a new generation of instrument-platform combinations. A promising near-term approach is a variant of the eddy correlation method, namely, the conditional sampling method, which slowly accumulates samples from the upward-moving eddies in one container and samples from the downward eddies in another.[22] After careful conditioning, the differences between the two containers can be measured with conventional slow-response instruments. For many of the questions about the mechanisms controlling global sources and sinks of infrared active gases, time-resolved full eddy correlation measurements are required.

Because of satellites' global coverage, they are an important element in this emerging strategy, particularly flexible small satellites that can implement new technical developments rapidly. Global databases gathered from such platforms would undoubtedly revolutionize our grasp of biogeochemical cycles, if these databases were intelligently linked to direct observations of flux—that is, strategically deployed ground-based and in situ observations of the infrared species. For public policy this approach may ultimately prove the only credible way to verify compliance with international emissions control agreements, if they were adopted. Requirements for such systems, for both accuracy (0.1 percent or better) and spatial resolution (0.5° or better with some vertically resolved information), are beyond currently available technology. High-precision remote sensing devices need to be developed and tested with in situ measurements.

Pilotless or robotic aircraft represent another emerging technology that could transform the study of greenhouse gases and be an important component in any systematic global approach to this measurement problem. Such aircraft could provide a platform for making near-continuous flux measurements over remote and inaccessible areas of the globe, such as the oceans, jungle, tundra, and icepack. To take advantage of this platform, however, lightweight instrumentation with fast response times and high accuracy must be developed. This instrumentation could be designed for in situ measurements at low altitudes within the boundary layer or for remote sensing measurements from high altitudes. These platforms will also provide an important link between broad-scale, detailed flux and concentration observations and a new generation of flexible small satellites.

Model Development

The need for model development to assess the long-term variability of biogenic greenhouse gases is severalfold. Improved global biological process models are critically needed to extrapolate from past intensive studies of limited domains in space and time to global and decadal space and timescales. The quality of such models is presently limited by the short duration of the field measurements on which they are based. Once based on longer-term field measurements, such as a those described above, these global models can then be driven by such parameters as temperatures and moisture and in some cases by satellite observations of vegetation.

Improved atmospheric chemical transport models are needed to better elucidate the effects of changing surface sources and sinks on atmospheric concentrations. While atmospheric models on all scales need improvement, particular attention must be given to subgrid-scale transport processes, such as turbulent mixing of the atmospheric boundary layer, and both shallow and deep convective transport. At present, most models do not incorporate the effects of ecosystems on atmospheric dynamics, for example, via evapotranspiration. Transport models that use assimilated winds also need to be improved and used in tropospheric applications to trace gas budgets in order to incorporate the effects of interannual variability in transport; such models will be essential for regional flux studies. Ocean models are also needed to integrate sparse oceanic data, thus clarifying biogeochemical cycles in the oceans, and to provide regional estimates of trace gas exchanges between the oceans and atmosphere. Ultimately, coupled biospheric, oceanic, and atmospheric models that allow for the proper feedbacks must be developed to reach the goal of predicting trends in biogenic greenhouse gases.

Establishing a Consistent Strategy for Determining Secular Trends in Ozone as an Infrared Active Species in the Mid- to Upper Troposphere and Lower Stratosphere

Ozone has a critical role as absorber of ultraviolet radiation in the stratosphere and in the oxidant chemistry of the troposphere, but additionally its absorption feature at 9.6 μm makes it an effective greenhouse gas when present in the upper troposphere and lower stratosphere. Thus, it is essential to document trends in ozone in the upper troposphere and lower stratosphere and the causes of these trends.

In situ measurements of the vertical distribution of O_3 are critical to characterizing long-term ozone trends in the upper troposphere and lower stratosphere; these measurements provide high vertical resolution and offer an independent check on remote sensing data. While there is an international ozone sonde program, the present set of ozone sonde stations does not provide a coherent or adequate program. The stations do not use the same techniques; not all maintain adequate calibration programs; and the frequency of measurements is too low at several stations. Some stations are located in sufficiently polluted locations that the quality of the tropospheric data may be compromised. Most important, the number of sites maintained under the current program is simply too few to provide a reliable global picture. A large number of sites is particularly critical in measuring upper-tropospheric O_3 because of its relatively short lifetime and the spatial heterogeneity in the sources of the chemical precursors of tropospheric O_3.

To make the current ozone sonde network adequate, many sites will need to be upgraded. In addition, at least 10 new sites must be added, primarily over the tropical continents and oceans. The planned Network for Detection of Stratospheric Change will not be adequate for detection of trends in the troposphere because its measurements will be oriented toward obtaining stratospheric data and there are too few sites (about six).

Because of the labor-intensive nature of sonde observations and the difficulty of reaching remote observing sites, there is a critical need to develop a consistent pattern of observations with high accuracy and high spatial resolution, since ozone varies significantly on small spatial scales in the troposphere. These observations must also be made on wisely selected trajectories, based on detailed meteorological predictions for the vicinity of the observations. Robotic aircraft may provide a unique contribution to this problem because they aid in selected locations for sonde deployment, automation of operations, and reductions in cost.

While in situ measurements provide data with high vertical resolution, space-based measurements provide global coverage. For this reason, maintenance and enhancement of satellite measurements of the ozone vertical profile are critical. Measurements from the Stratospheric Aerosol and Gas Experiment (SAGE) II have provided valuable information on ozone trends above 17 km since 1984, with the exception of the period after the Pinatubo volcanic eruption, when data could not be obtained in the lower stratosphere. Launch of a new instrument while SAGE II is operational (e.g., SAGE III) would allow for overlap and lead to more reliably described trends in the future. Gaps in ozone observations have been a serious problem.

Unfortunately, while extremely useful for inferring ozone trends in the stratosphere, SAGE II does not yield data on ozone in the upper troposphere. Combining data from the Total Ozone Mapping Spectrometer and SAGE II has proved useful in inferring tropospheric nitrate and ozone column concentrations,[23] but the lack of vertical resolution and gaps in the data record make this technique of limited use for tracking upper-tropospheric O_3 trends. On the other hand, newly available remote sensing techniques could form the basis for such space-based measurements of tropospheric O_3.

Mid- to Upper-Tropospheric Water Vapor: Understanding the Distribution of the Dominant Infrared Active Molecule in the Climate System

Water in its various phases constitutes the critical link between the chemical component of global change and the dynamics, radiation, and climate components. First, water in the vapor phase is the first-order source term for hydrogen radicals (augmented in the midtroposphere by hydrocarbon and peroxide photochemistry), which in turn determine the photochemical production rate for ozone in a given volume element in both the troposphere and the stratosphere. Water in aerosol form provides the site for surface catalysis that repartitions the dominant chemical families in the troposphere and the stratosphere and alters the chemical composition (and thus the formation characteristics) of the aerosol particles themselves. As the temperature drops in the upper troposphere, particularly in the tropics and polar regions, the rate of chemical transformation increases exponentially, in some important cases by as much as three orders of magnitude over an interval of 10°C. The formation of cirrus, both visible and subvisible, is driven by the combination of water vapor density, temperature, pressure, organic aerosols, and sulfate/nitrate loading. The role that cirrus formation plays in the climate system is a critical quantitative question but one for which little information exists. An understanding of water vapor in its phases has emerged as the main link between chemistry, radiation, dynamics, and climate. Progress in clarifying these relationships will depend on a strategic blend of in situ and remote observations that explore the links among sea surface temperature, convective drive, horizontal water vapor redistribution, and mechanisms controlling the ratio of dry subsidence regions and moist vertically ascending zones in the climate system. A consistent attack on this problem is needed, using a combination of sonde and aircraft observations with an array of chemical tracers and isotopes, together with innovative satellite observations.

For the purpose of initially determining secular trends in water, in situ measurements (using sondes with improved accuracy and more fully instrumented aircraft) offer the advantage of high vertical resolution and provide a test of existing satellite data.

Instruments such as SAGE II,[24] the Halogen Occultation Experiment, and the Microwave Limb Sounder on the Upper Atmosphere Research Satellite have demonstrated that stratospheric water vapor can be measured from satellites with adequate precision to characterize temporal trends at some levels. Because of the global coverage that space-based platforms provide, continuous measurements using these techniques are critical for tracking the potential causes and effects of global climate change.

Compared to H_2O concentrations typically found in the lower and midtroposphere, such concentrations in the upper troposphere are extremely small. (H_2O concentrations from the surface to the tropopause typically decrease by about three orders of magnitude or more.) As a result, the technologies used for routine weather soundings do not have the accuracy or the sensitivity to reliably monitor H_2O in the upper troposphere. Moreover, current space-based platforms (e.g., SAGE II) are only able to quantify upper tropospheric H_2O when aerosol loadings are low.[25] For these reasons, new approaches must be developed for measuring H_2O trends in the upper troposphere. Ideally, these approaches would be amenable to remote sensing from small satellite platforms, thus affording a strategy for obtaining global coverage at a reasonable cost.

Photochemical Oxidants

Global change arises as molecules, released largely at ground level, amplify or suppress oxidation patterns in the troposphere. These processes occur on urban, regional, and global scales, linked by a network of reactions. The reaction network engages homogeneous gas-phase catalysis, photolysis, heterogeneous transformations, and gas-to-particle conversion, all superimposed on a chaotic dynamical pattern. To map individual air mass motion in this pattern alone requires complex use of tracers.

Understanding of the distribution and trends in photochemical oxidants, as well as the network of reactions that dictate production and loss rates, is not yet in hand. Thus, there is relatively little ability to conduct rigorous integrated assessments of oxidant levels, health impacts, lifetimes of species released into the troposphere, and degradation pathways to terminal products—all central features of global change.

Elevated oxidants on urban and regional scales in industrialized countries are proving among the most intractable of air quality and global change problems. Related information is critical in making economic and health decisions. One goal of atmospheric chemistry research must be the better definition of mechanisms that determine the distribution and secular trends of these photochemical oxidants. This imperative has two principal objectives: (1) to understand the ability of the atmosphere to produce and destroy ozone, both now and in the decades ahead, and (2) more specifically, to understand the ability of the atmosphere to cleanse itself, via free radical oxidation, both now and in the future.

Free-Radical-Catalyzed Removal of Source Molecules: Hydroxyl Radicals and Other Oxidizers

One of nature's most important and ingenious systems for cracking the structure of a wide spectrum of molecules is via an initial oxidation step that is to some extent counterintuitive. This system depends in large part on a single chemical species—the OH radical that is present at a mole fraction of $\sim 10^{-13}$, a tenth of a part per trillion. This mechanism places great importance on understanding the relationship between the hydroxyl concentration and its primary production and loss processes. Corresponding measurements present a serious combination of demands: detection thresholds in the parts-per-quadrillion range; high spatial resolution (0.1 km) such that establishing covariance with hypothesized source and sink molecules is possible; consistent observational methods that can cover the altitude range from the surface to the tropopause; observational ranges that can identify the major domains of tropospheric chemical character (e.g., the biomass-burning regions of the African/South American axis, the pristine marine environment of the western tropical Pacific region, the industrial regions of China, western Europe, and the Americas); and simultaneous observations of tracers that uniquely identify the characteristic regions.

To what extent do other oxidants such as NO_x, H_2O_2, and halogen atoms determine oxidation rates? How do changes in ultraviolet exposure, temperature, convection drive, severe storms, aerosols, cloud cover, and rainfall patterns in the troposphere—on urban, regional, and global scales—shape oxidation patterns? Attacking this set of questions has proven both difficult and necessary. It requires a step forward in innovation—the deployment of lightweight rugged instruments at remote sites on aircraft (piloted and robotic), carried out in conjunction with strategic satellite observations and the development of innovative models.

Nitrogen Oxides and Ozone: Precursors and Oxidizers

Research on the medical impacts and biological responses of terrestrial systems to polluted air masses invariably turns to the question of ozone and the species responsible for its production. The fact that ozone is catalytically destroyed in the stratosphere by free radicals but catalytically produced in the troposphere by free radicals is both a cornerstone in our understanding and a challenge to global-scale studies. What are the predominant instigators of ozone production? What fraction of ozone precursors is emitted from natural (biogenic) sources and how do these sources change with meteorological conditions, land use, sulfates/nitrate loading, and other factors? What fraction of tropospheric ozone is imported from the stratosphere? What fraction is produced globally by lightning via NO_x production? How do the specifics of urban pollution events affect the global source of tropospheric ozone? How is the NO_x/NO_y system partitioned in various regions of the troposphere? How does the mix of volatile organics, carbon monoxide, and nitrogen oxides affect the source strength of ozone?

Unfortunately, to date, photochemical oxidant research is truly data poor and measurement limited. Significant progress in this area will require the acquisition of high-quality observational datasets that are global in coverage as a whole but of high enough spatial and temporal resolution individually to clarify the chemical and physical processes in the production, transport, and removal of photochemical oxidants. Laboratory studies also play a central role in all aspects of atmospheric chemistry but particularly with regard to photochemical oxidants and in tropospheric chemistry. In short, a research strategy that is both evolutionary and revolutionary will be required—a strategy that is outlined below.

The key reactions relating to photochemical oxidants take place under a wide range of conditions: on salt spray in the presence of high fluxes of solar ultraviolet radiation; in biomass-burning plumes with a rich variety of organics, sulfur, aerosols, moisture, and other constituents; in clean marine regions nearly devoid of NO_x but with very high levels of water vapor and ultraviolet; and in cold high-latitude regions, where heterogeneous reactions on micron-sized ice crystals catalyze inorganic chlorine and bromine to free radical precursors. The intrinsic dynamic instability of the troposphere interacts with these regions on timescales of weeks, such that observational trajectories must be tactically selected to track volume elements in a Lagrangian frame. Moreover, chemical time constants linking species are typically 10 days or more. Thus, observations must be pursued in the context of local trajectory patterns defined by meteorological analysis.

As altitudes approaching the tropopause are investigated, there is increasing opportunity to use strategically designed satellite observations to simultaneously observe O_3, H_2O, and associated tracers such as N_2O, CH_4, and CFC-11.

Instrument development and validation should aim at improving the sensitivity, specificity, and sampling rates of instruments needed to measure the compounds of interest throughout the atmosphere from the measurement platforms of choice. Development should focus on several areas:

- simpler and more reliable instruments to be used in long-term monitoring;
- miniaturization of instruments, to accommodate a wide array of measurements on airborne platforms;
- continuous, fast-response instruments to be used for flux measurements and in airborne applications;
- the use of spatially resolved long-path methods (e.g., LIDAR (light detection and ranging instrument)) that can be operated from airborne and mobile platforms to determine one- and two-dimensional distributions of compounds of interest over considerable distances from the emitter/detector units;
- innovative aircraft platforms that can follow specific trajectories using fast-response instruments; and
- innovative small satellites.

Integrated Field Campaigns: The Union of Chemical, Radiation, Dynamics, and Technology

Integrated field campaigns increase our understanding of fundamental atmospheric processes; elucidate the distributions, sources, and sinks of key species; and provide the data to evaluate air quality and chemical transport models. Any specific field campaign must be designed carefully with regard to the scientific questions it addresses and the uncertainties it must minimize. Atmospheric chemistry and meteorology must be integrated in the planning and deployment of air quality measurements and monitoring. The questions now before us will require multidisciplinary teams to consider chemistry, transport, and ecosystem feedbacks. Modeling tools adequate to depict or simulate these processes must be available to guide the planning of measurements as well as the interpretation of results. Moreover, an adequate fleet of research aircraft must be available to the atmospheric sciences community to make these studies feasible.

Carefully designed observations (with or without specific tracer compounds or suites of tracer compounds) can be used in conjunction with diagnostic and/or observation-based models to independently infer a number of phenomena: long-term trends and regional and seasonal variability in short-lived free radical species not amenable to continuous, spatially extensive monitoring; urban, regional, and global-scale emission inventories of ozone precursors; and the sensitivity of ozone and other photochemical oxidants to ozone precursor compounds. At the same time, the diagnostic and observation-based interpretation of field measurements will require adequate laboratory definition of the fundamental mechanisms involved in atmospheric processes.

The development and deployment of monitoring networks, along with analysis of resulting data, are needed to establish the chemical climatology of ozone, other photochemical oxidants, and their precursors. This climatology will help establish temporal and spatial trends and shorten the time required to unequivocally observe a response in ozone to changes in the concentration of its precursor compounds. These networks must include components capturing the roles that meteorology and dynamics play in the redistribution of airborne chemicals. Moreover, a comprehensive chemical climatology for photochemical oxidants must include data from the free troposphere as well as the surface. It is thus likely that these networks will require the use of balloon sondes, robotic aircraft, and space-based platforms in conjunction with newly developed instrumentation based on small, lightweight, low-power technology.

Linking Scientific Results with Integrated Assessments

Integrated assessments draw from a wide range of scientific information and disciplines to provide more comprehensive guidance on scientific and technical matters to the decision-making community. The research strategy in atmospheric chemistry should support these assessments by providing analytical and modeling tools that can readily support these integrated assessments.

Atmospheric Aerosols and UV/Visible Radiation

Compelling evidence has emerged that aerosols play a central role in control of both the UV/visible exposure at the Earth's surface and the balance between albedo and retention of infrared radiation in the atmosphere. Aerosols demand specific attention.

Minute amounts of particulate matter in the stratosphere, along with increased levels of anthropogenic chlorine, are responsible for the Antarctic ozone hole and probably for the less dramatic but nevertheless significant global-scale ozone depletion. The atmospheric haze associated with industrial activity near major cities is now believed to partially mask the expected increase in surface temperature associated with greenhouse gas increases. Atmospheric aerosols also

BOX 5.8 Critical Scientific Questions for Atmospheric Aerosols

1. What is the role of natural and anthropogenic aerosols in climate and how will future changes in the levels of aerosol precursors affect this role?
2. How will future natural and anthropogenic aerosols affect stratospheric and tropospheric ozone and the cleansing capacity of the atmosphere?
3. What is the role of atmospheric chemistry in changing the composition of aerosols that affect human health, the environment, visibility, and infrastructural materials?

have important impacts on human health, quality of life, and materials degradation. Yet despite these recent advances in appreciating the importance of atmospheric aerosols, our understanding of these critical species is in its infancy. We do not comprehend the impacts of aerosols now and cannot now predict how those impacts will change in the future through human activities.

Several important questions must be addressed about the effects of atmospheric aerosols on climate, atmospheric chemistry, and human health and well-being (see Box 5.8).

To answer these questions, we must go far beyond our current state of knowledge of atmospheric aerosols. Further details of the needed research strategy can be found in *A Plan for a Research Program on Aerosol Radiative Forcing and Climate Change* (NRC 1996).

Stratospheric Aerosols

Limb scanning of solar extinction from satellites has been very successful in monitoring the global stratospheric sulfate layer and its spatial and temporal response to volcanic perturbations. Combined with in situ measurements of particle size distributions from balloons and stratospheric aircraft for validation, satellite multiwavelength extinction measurements have determined the surface areas of stratospheric aerosol particles with an accuracy adequate for heterogeneous chemical applications. New instruments with higher-wavelength resolution, possibly deployed on small satellites, will be the main monitoring tool for this component in the future.

Tropospheric Aerosols

The complexity of the tropospheric aerosol presents a considerably more difficult problem. Past in situ measurements focused on determining the size distribution or chemical composition of aerosols at specific locations. Several new techniques under development are probing the chemical composition of single aerosol particles. However, these measurements are essentially point measurements, with little information about spatial and temporal variability. Moreover, methods for analyzing the composition of organic aerosols, arising, for example, from biomass burning or urban pollution, are incomplete. Clearly, new in situ instrumentation is needed to quantitatively document the complex chemical composition of tropospheric aerosols over their full size range in the various regions of the globe of interest for atmospheric chemistry.

Current remote sensing technology allows the measurement of gross tropospheric aerosol parameters over large spatial regions but not such features as composition or a complete size distribution. Technologies such as scanning polarimeters in the visible and near infrared appear able to retrieve tropospheric aerosol scattering characteristics from measurements of multispectral radiance and polarization by resolving aerosols from clouds and thus hold promise. Moreover, surface and airborne LIDAR can be used to map tropospheric aerosol backscatter and, combined with Raman measurement of scattering, can provide limited information about aerosol characteristics. Preliminary measurements with nadir-viewing LIDAR from the U.S. Space Shuttle show promise for obtaining detailed gross features of tropospheric aerosols on a global basis.

With the development of new instrumentation, monitoring networks will be needed to document the spatial and temporal trends in key aerosol characteristics. These characteristics include aerosol number, size, distribution, chemical (and toxic) composition, and radiative properties. Moreover the networks must be designed to address a variety of issues on urban, regional, and global scales. For example, on urban scales, monitoring networks are needed to uncover the characteristics of aerosols that lead to pulmonary health effects in humans. On regional scales they are needed to clarify the relationships between aerosol precursor species and visibility, and on global scales they are needed to better characterize quantitative relationships between aerosols and climatic effects.

The Strategy of Observations and Calculations

To predict how future human activities are likely to affect atmospheric aerosols and the related impacts on climate, chemistry, and human health, we must go beyond an aerosol climatology to a deeper understanding of the processes that control aerosol formation, transformation, and removal. This advance will require the design and implementation of intensive field programs that bring together chemical and physical aerosol measurements and precursor gas studies using surface, aircraft, and ship measurements.

In this regard two novel experimental strategies have emerged for resolving some of the most important questions concerning tropospheric aerosols and their effects. The first is the "closure experiment," in which an overdetermined set of variables is measured. A subset of the observations and the relevant theories is then used to predict values for a "closure variable," which is also measured independently. The result is a test of both measurements and theory and an opportunity to evaluate the quality of our understanding. With the instrumentation now available, closure experiments can be performed on aerosol number concentration (using a variety of sizing instruments), mass (based on measurements of relevant inorganic and organic species), radiative properties (using chemical composition, relative humidity, and Mie theory), and the integrated column effect of aerosols on short- and long-wave radiation. Closure experiments on aerosol mass can help answer questions about chemical composition, since missing species will make closure impossible. Theories about the impacts of aerosols on radiative climate forcing can also be tested by local and column closure experiments. Most of the aerosol experiments planned for the next decade depend heavily on this strategy because it offers a rigorous test of both measurements and the process models on which more comprehensive models depend.

The other new observational strategy is to observe the evolution of aerosols and their precursor gases in a Lagrangian reference frame. The idea of Lagrangian experiments is not new, and variations on this theme have been used occasionally. Recently, however, there has been considerable work on tagging air masses with balloons and chemical tracers, so that aircraft carrying large suites of instruments can revisit the air mass over a period of days to observe changes with time. Although these experiments cannot eliminate the effects of dispersion and vertical mixing on concentrations, with ample dynamical measurements, they make it possible to sort out the chemical and physical processes that cause changes in aerosols. These processes include gas-to-particle conversion, chemical transformations, wet and dry deposition, entrapment of air from other strata, and mixing through the sides of the "air mass" (dispersion). These experiments tend to be complex and expensive (at least one ship and one or two aircraft are required), but they offer the potential to test the aerosol models that now exist and that will be developed from future laboratory work and other process studies.

The overall strategic goal for the next two decades should be a predictive model to calculate atmospheric temperature and chemical species concentration fields and from that information to derive new aerosol particle formation rates and predict the chemical content and size distribution of the aerosol fields. Because current atmospheric models generally impose rather than predict aerosol distributions, significantly more sophistication will be needed in future models to represent precursor gas and gas/particle kinetics, nucleation and agglomeration kinetics, and vapor/particle interactions. One way to stimulate the needed improvements in aerosol modeling is to encourage the modeling community to participate directly in the planning, execution, and data analysis for the strategic field measurement programs described above.

Furthermore, predictive aerosol models will require currently unavailable quantitative mechanistic and kinetic input data describing a large number of heterogeneous growth, nucleation, agglomeration, and accommodation/evaporation processes. These quantitative input data will have to come from a vigorous laboratory program in heterogeneous kinetics and aerosol microphysics.

Toxics and Nutrients

The atmosphere and biosphere are fundamentally coupled through the exchange of gases and aerosols. Ecological systems, including those of economic import (e.g., those dedicated to agriculture and forestry), can be profoundly affected by the wet and dry deposition of both toxic and nutritive atmospheric substances. While many of the atmosphere's naturally occurring components can have toxic and/or nutritive effects on the biosphere, there are myriad toxic and nutritive substances in the atmosphere that are significantly shaped by industrial and agricultural activities. Moreover, while we are beginning to identify more acute cases of atmospheric toxicity and overfertilization for critical ecosystems, our understanding is far too limited to assess the extent of these problems now and to predict future ones.

In its most general form the motivating scientific question for the study of toxics and nutrients is: How are interactions between the atmosphere and biosphere influenced by the changing atmospheric concentrations of these substances and by the deposition of harmful and beneficial compounds? More specifically, from the viewpoint of atmospheric chemistry, this question can be posed as: What are the rates at which biologically important atmospheric trace species are transferred from the atmosphere to terrestrial and marine ecosystems through dry and wet deposition? The essential elements of a research strategy to address this question are outlined below.

Toxic and Nutrient Impacts: The Measurement of Deposition Fluxes

Many of the key issues for toxics and nutrients cannot be satisfactorily answered yet because we lack methods to measure deposition fluxes on appropriate spatial and temporal scales. This problem is most severe for dry deposition, where technologies for reliably measuring many of the most biologically important fluxes do not yet exist. Adequate support for technique development in this area is thus a critical need; relaxed eddy accumulation, eddy correlation, and gradient methods offer particular promise.

In the case of wet deposition, reliable techniques have been developed in principle, but serious questions remain about sampling representativeness and contamination. The problem is most acute for measuring wet deposition fluxes over the ocean, where it is virtually impossible to collect uncontaminated rain samples from a buoy in midocean, while samples from shipboard platforms are necessarily intermittent. Present marine deposition estimates, often the result of comparing model calculations with a very small set of shipboard and island observations, are typically subject to uncertainties of a factor of three or more. The development of new techniques for more representative determination of wet as well as dry deposition fluxes, perhaps from a low-flying airborne platform, must therefore also be considered a high priority.

In some instances, such as in high-altitude forests and foggy regions, the deposition of cloud droplets may be the primary avenue by which toxics and nutrients are delivered to the Earth's surface.[26] It is extremely difficult to measure such fluxes because the droplets are so transient that their flux is easily altered by the presence of measuring devices. Thus, new methodologies need to be developed to assess the importance of droplet deposition and to provide reliable flux measurements.

In the recent past, deposition monitoring networks have proven useful in determining the ecological impacts of atmospheric deposition (e.g., the National Acid Deposition Program/National Trends Network). However, these networks have mostly been limited to monitoring the deposition of a specific chemical or class of compounds (e.g., acid deposition, ozone). For this reason these networks have provided very limited information on the stresses and benefits experienced by an ecosystem from atmospheric deposition and thus on the long-term effects of this deposition as well. With the development of new deposition measurement techniques, it should be possible to design more comprehensive atmospheric deposition/exposure monitoring networks. Implementation of these networks for key ecosystems would provide a long-term record of atmospheric deposition; with colocated ecological monitoring, this record would no doubt prove useful in establishing causal relationships between atmospheric deposition and ecosystems' vitality and succession.

Toxics and Nutrients: Processes and Mechanisms Leading to Deposition

Even with reliable and fully evaluated deposition measurement techniques, it will never be possible to measure dry and wet fluxes for all species of interest over all ecosystems of interest, over all time. Consequently, process-oriented field studies, which make observations of fluxes under carefully selected ranges of conditions, must be undertaken to identify the factors that control fluxes. With these factors identified, algorithms and parameterizations describing deposition fluxes could be developed, tested by further observations, and incorporated into regional and global atmospheric chemistry models, as well as integrated atmospheric/biospheric response models.

NOTES

1. NRC (1992).
2. Farman et al. (1985).
3. Anderson et al. (1991).

4. Brune et al. (1991).
5. Weinheimer et al. (1998).
6. Johnson (1971).
7. Climate Impact Assessment Program (1975).
8. Fahey et al. (1995).
9. Johnson (1971).
10. Wennberg et al. (1994).
11. Fahey et al. (1995), Hanisco et al. (1997).
12. See review by Holton et al. (1995).
13. Plumb and Ko (1992).
14. NRC (1992).
15. Ibid.
16. Seinfeld and Pandis (1998).
17. Prather (1985, 1986).
18. Ibid.
19. Prather et al. (1987).
20. E.g., Baldocci et al. (1996).
21. Tans et al. (1996).
22. Businger and Oncley (1990).
23. Fishman et al. (1990).
24. McCormick (1993).
25. Ibid., Rind et al. (1993).
26. Vong et al. (1991).

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6

Paleoclimate Overview

SUMMARY

The task of understanding climate change and predicting future change would be complex enough if only natural forcing mechanisms were involved. It is significantly more daunting because of the introduction of anthropogenic forcing and even more so considering the limitations in available records. Earth history provides a unique opportunity to assess the temporal and spatial characteristics of climate variability prior to any anthropogenic forcing; assess the natural rates of change associated with the evolution of the Earth system to understand how physical and biospheric systems interact across multiple time- and space scales; define the nature of the sensitivity of the Earth's climate and biosphere to a large number of forcing factors; examine the integrated climatic, chemical, and biological response of the Earth system to a variety of perturbations; and test the predictions of numerical models for conditions significantly different from the present day. In effect, the paleoclimate record provides a series of cases and lessons upon which our understanding of climate change can be constructed and tested.

The paleo perspective has provided some significant surprises concerning climate change, changes in atmospheric chemistry, and the response of natural systems to climate change. The most recent dramatic new discovery is the verification that rapid and massive reorganizations in the ocean-atmosphere system—rapid climate change events—have occurred at frequent intervals throughout at least the last glacial cycle (the past ~100,000 years). The largest of these events are characterized by changes in climate that are close to the order of glacial/interglacial cycles. Perhaps most surprising is the demonstration that these rapid climate change events turn on and off in decades or less and may last centuries to millennia. Furthermore, these events are globally distributed and

found in a variety of paleoenvironments (ocean, atmosphere, and land). Several potential causes for these events have been proposed, but without a more detailed understanding of the relative phasing of these events from region to region, definitive causal mechanisms cannot be constructed.

Of greatest consequence to humans is the fact that subdued versions of these events are documented during our current interglacial (the Holocene, which began ~11,500 years ago[a]). While subdued relative to earlier events, they are still sufficient to significantly perturb natural systems and still operate at rapid rates (years to decades). Thus, one of the most important tasks for paleoclimatologists is to improve our understanding of Holocene climate, for it is within the Holocene that the boundary conditions for modern natural climate variability can be identified and from which the relative importance of natural versus anthropogenic climate forcing can be assessed.

Patterns in climate variability can be identified on the interannual to millennial scale. This finding is particularly encouraging since one of the end goals of climate change research is predictability. However, deconvolving predictable patterns at the regional scale and determining the temporal baseline from which predictability can be assessed will require more dense spacing of paleodata.

Few instrumental records precede the era of anthropogenic involvement; thus, it is necessary to supplement and hindcast these data with paleoclimate records. The intended meaning of hindcast is to extend instrumental time series back prior to their onset date using proxy records. The assumption is made that a transfer function of some type links the instrumental and proxy records allowing this process. Fortunately, many paleodata series afford detailed views of pertinent climate indicators (e.g., temperature, precipitation, El Niño-Southern Oscillation (ENSO), monsoon). On the other hand, since there are no true analogs in the paleoclimate record for modern or future climate, it is essential to utilize both modern observational and paleoclimate records to solve this complex problem.

New advances in paleoclimate research reaffirm the necessity to view climate change over varying timescales; utilize a variety of globally distributed paleoclimate records that monitor change throughout the Earth system; and focus attention on well-dated, highly resolved multivariate paleoclimate records. These paleodata are essential for understanding global environmental change and its potential impact on humans, assessing human influence on the global environment and for the evaluation of predictive climate models.

The research imperatives for paleoclimate are to:

- Document how the global climate and the Earth's environment have changed in the past and determine the factors that caused these changes. Explore how this knowledge can be applied to understand future climate and environmental change.

[a] Assumed format is calendar years unless specified as ^{14}C years.

- Document how the activities of humans have affected the global environment and climate and determine how these effects can be differentiated from natural variability. Describe what constitutes the natural environment prior to human intervention.
- Explore the question of what the natural limits (e.g., in the frequency of events, trends, extremes) are of the global environment and determine how changes in the boundary conditions (e.g., greenhouse gases, ocean circulation, ice extent) for this natural environment are manifested.
- Document the important forcing factors (e.g., greenhouse gases, solar variability, ocean circulation, volcanic aerosols) that are and will control climate change on societal timescales (season to century). Determine what the causes were of the rapid climate change events and rapid transitions in climate state.

INTRODUCTION

Since ancient times humans have modified their local and regional environments, but only since the Industrial Revolution has human activity had a significant measured effect at the planetary scale. Human impact on the composition of the global atmosphere is now without question. Human disturbance of biogeochemical cycles may now be approaching a critical level. Over the past few decades concentrations of atmospheric gases (e.g., CO_2, CH_4, N_2O) have been increasing dramatically and have moved into a range unprecedented for the past million years. This increase has produced serious concern regarding the heat balance of the global atmosphere. Greenhouse gases are, however, only part of the human problem. For example, sulfur gases and dusts can reinforce or counteract greenhouse gas effects on local to regional scales. While remarkable efforts are under way to resolve the history and significance of the human influences on climate, pollution, and resource depletion, our understanding of climate change is still hampered by a lack of knowledge of the processes that underlie natural climate variations.

The importance of understanding natural climate variability has been clearly articulated in previous National Research Council (NRC) reports. In a 1975 report prepared by the U.S. Committee for the Global Atmospheric Research Program, documentation is provided for the presence of seasonal to millennial scales of natural climate variability and for regularities in climatic series. In the 1990 report the Committee on Global Change summarized several important contributions to the understanding of natural climate variability made by a variety of major scientific efforts that had emerged since the 1975 report. For example, the CLIMAP (Climate Mapping, Analysis, and Prediction) group produced the first comprehensive reconstructions of the Earth's climate during the last glacial maximum; the COHMAP (Cooperative Holocene Mapping Project) group extended paleoclimatic reconstructions to the post-glacial era and demonstrated the emergence of the African-Asian monsoon system; and the SPECMAP (Spectral Mapping Project) group verified the strong relationship between the Earth's orbitally induced cycles of insolation and major fluctuations in climate.[1] Since the 1990 NRC report several important discoveries have been made that have focused even more attention on the paleoclimate record.

The most dramatic of these new discoveries is the verification that rapid and massive reorganizations in the ocean-atmosphere system—rapid climate change events—have occurred at frequent intervals throughout at least the last glacial cycle (the past ~100,000 years). The largest of these events are characterized by changes in climate that are close to the order of glacial/interglacial cycles. Perhaps most surprising is the demonstration that these events initiate and terminate in decades or less and may last centuries to millennia. Of greatest consequence, however, is the fact that subdued versions of these events are documented during our current interglacial (the Holocene, which began ~11,500 years ago). Thus, these rapid climate change events have immense significance to our understanding of both natural climate variability and modern climate.

While the causes of rapid climate change events and natural climate variability, in general, are still not fully understood, evidence continues to accumulate emphasizing the significance of a variety of climate processes, such as changes in thermohaline circulation of the world's oceans, Earth's orbitally induced (Milankovitch) cycles of insolation, solar variability, greenhouse gases, volcanic activity, and ice sheet dynamics.

CASE STUDIES

This report focuses on five case studies chosen to demonstrate the potential wealth of information available from the paleorecord. The first three are presented in specific time domains (the last glacial cycle to onset of the Holocene; the Holocene; the past 2,000 years of the Holocene). The last two focus on subject areas that draw on a wide range of Earth history—namely, climate-vegetation interactions and warm climates.

The Last Glacial Cycle to the Onset of the Holocene (~11,500 years ago)

Summary of Previous Work

A variety of paleoclimate records demonstrate that the Earth's climate has varied significantly throughout the past 1 million years. This natural climate variability ranges from glacial to interglacial states, in approximately 100,000-year cycles that terminate as ~10,000-year-long interglacials, characterized by relatively ice free and warm conditions.[2]

Knowledge of the low-frequency component of the Earth's climate variabil-

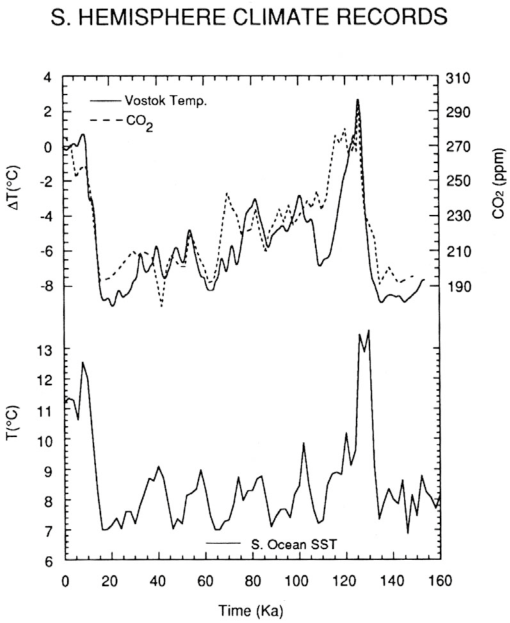

FIGURE 6.1 Comparison of three high-latitude records from the southern hemisphere showing the overall good agreement between CO_2 and temperature changes (inferred from δD). Taken from Crowley and North (1990). Data sources: the Vostok δD record (Jouzel et al., 1987) and the CO_2 record (Barnola et al., 1987) are plotted according to the revised chronology of Petit et al. (1990). SOURCE: Crowley and North (1990). Courtesy of Oxford University Press.

ity, resulting from changes in the Earth's orbital cycles, pioneered by the CLIMAP project and described by Imbrie et al. (1992, 1993), has been verified and further elucidated by the SPECMAP project. Orbitally induced variations in insolation at the Milankovitch periods (primarily 100,000, 41,000 and 23,000 years) explain much of the change in global ice volume throughout the late Pleistocene and have been identified in a variety of paleoclimate records (e.g., marine and ice cores and loess sequences). CO_2 and CH_4 figure prominently in climate change over the last glacial/interglacial cycle, as demonstrated by the close association between Vostok (Antarctica) ice core CO_2 and temperature (see Figure 6.1).[3] This dramatic demonstration of the long-term association between temperature and CO_2 has had a profound effect on the implications of anthropogenically induced greenhouse gas warming. However, the fact that CO_2 lags temperature at major climate transitions (e.g., the end of the last interglacial) suggests that the system response may be complex.

New Developments

The most dramatic recent contributions to our understanding of paleoclimate during the last glacial cycle have come in the millennial-scale range of climate variability. Unprecedented swings in the Earth's climate have now been recorded in two ice cores from central Greenland, instigating new higher-resolution investigations of land and marine paleoclimate records.

In 1993 the Greenland Ice Sheet Project Two (GISP2) successfully completed drilling to the base of the Greenland ice sheet in central Greenland. In so doing, GISP2, along with its European companion project GRIP (Greenland Ice Core Program), developed the longest high-resolution continuous paleoenvironmental record (>250,000 years) available from the northern hemisphere. Based on the comparison of electrical conductivity and oxygen isotope series between the two cores,[4] at least the upper 90 percent displays extremely similar if not absolutely equivalent records.

The central Greenland ice cores provide a framework for other paleoclimate records because of their relatively precise dating. The current best estimate of the age at ~2,800 m is ~110,000 years, based on a combination of multiparameter annual layer counting combined with measurements of the $d^{18}O$ of atmospheric O_2 calibrated with the Vostok ice core in Antarctica.[5] Error estimates in the dating are quite remarkable, from 2 percent for 0 to11,640 years ago to 10 percent for over 40,000 years.[6] Agreement between the GISP2 and GRIP ice cores (separated by 30 km or ~10 ice thicknesses) over the record period of the past ~110,000 years provides strong support for the climatic origin of even the minor features of these records and implies that investigations of subtle environmental signals can be rigorously pursued. The climatic significance of the deeper part of these ice cores (>110,000 years in age) is a matter of considerable controversy. Without additional records, the evidence for rapid climate change in Greenland during the last interglacial remains equivocal.

The millennial-scale events recorded in the upper 110,000 years of the two central Greenland ice cores are, however, unequivocally climate events. They represent large climate deviations (massive reorganizations of the ocean-atmosphere system) that occur over decades or less and during which ice-age temperatures in central Greenland may have been as much as 20°C colder than today (see Figure 6.2).[7] These events have their greatest magnitude during the glacial portion of the record, prior to ~14,500 years ago), when large northern hemisphere ice sheets provided positive climate feedbacks.[8]

Examination of one of these events, the Younger Dryas (a near return to glacial conditions during the last deglaciation, previously identified in a variety of paleoclimate records), demonstrates the importance of conducting multiparameter high-resolution paleoclimate investigations on well-dated records. During this event lowered temperatures were accompanied by up to twofold and greater changes in snow accumulation, order-of-magnitude changes in the amount

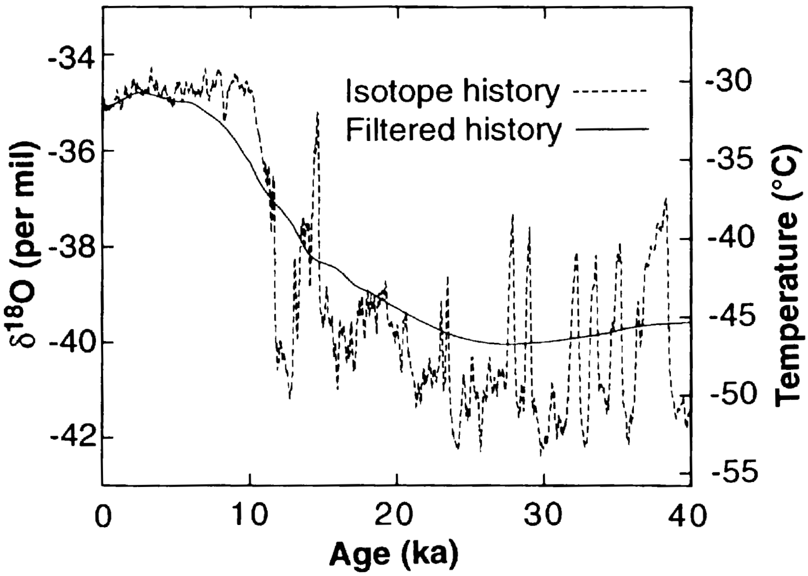

FIGURE 6.2 The central Greenland $\delta^{18}O$ history for the most recent 40,000 years. The smooth curve results when this history is filtered to mimic the thermal averaging in the ice sheet. All temperature histories that give this same curve when filtered are indistinguishable to borehole thermometry. The right axis shows the calibrated temperature scale. SOURCE: Cuffey et al. (1995). Courtesy of the American Association for the Advancement of Science.

of wind-blown dust and sea salt in the atmosphere, and large changes in methane concentration, with cold, dry, dusty, conditions correlated with low-methane (see Figure 6.3).[9] Annually resolved sampling over early and late stages of the Younger Dryas indicates that this ~1,300-year duration event began and ended in less than 5 to 20 years.[10]

The identification of rapid climate change event style variations in the GRIP CH_4 record[11] (see Figure 6.4) prompted considerable interest in the identification of such events in other regions since the source areas for CH_4 during the last glaciation may have been in the middle to lower latitudes. In addition, several rapid climate change events recorded in Greenland are in the isotopic temperature record of the Vostok ice core from central East Antarctica, although with apparently smaller amplitude than in Greenland (see Figure 6.5).[12]

Paleoclimate records from North Atlantic marine sediment cores also contain notable millennial-scale variability,[13] although the exact timing of these events is less precisely known than for the Greenland ice cores. Several of the marine cores reveal evidence that the formation of NADW (North Atlantic deep water; warm, saline, nutrient-depleted deep return flow water), and thus the oce-

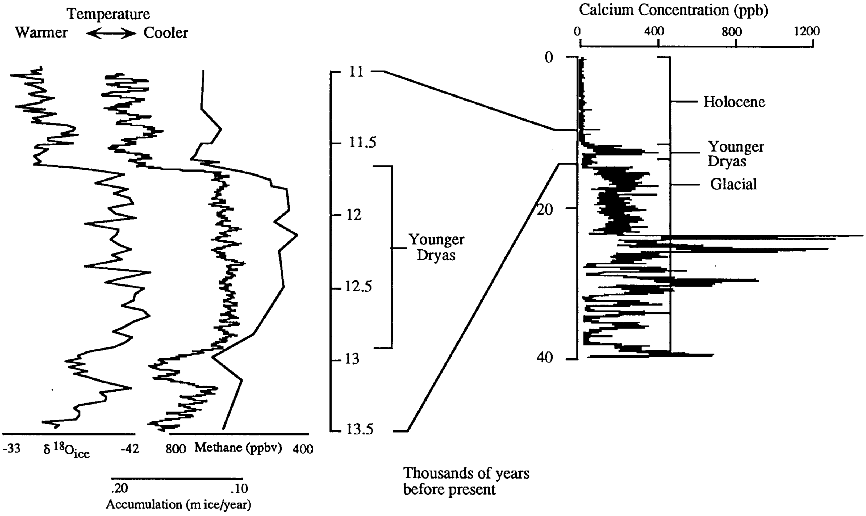

FIGURE 6.3 Composite figure. Above: the Younger Dryas was an abrupt return to near-glacial conditions (about 7°C lower, decreased accumulation rate, decreased methane, increased atmospheric dust) that lasted approximately 1,300 years and punctuated the transition from glacial to interglacial climates. Figure modified from Alley et al. (1993), Grootes et al., (1993), and Brook et al. (1996). Right: This high-resolution calcium record from the GISP2 ice core indicates the relative amount of dust in the atmosphere over Greenland and thus documents other abrupt, frequent, and massive changes in climate that characterize the glacial portion of the ice core record. SOURCE: Adapted from Mayewski et al. (1994, 1997). Courtesy of the American Association for the Advancement of Science.

anic thermohaline circulation, fluctuated dramatically in the past.[14] NADW diminished greatly during the last glaciation and was relatively strong during the interglacials. Recent studies confirm that NADW fluctuates on millennial timescales and correlates with sea surface and atmospheric temperatures.[15]

Changes in the flux of ice-rafted detritus, d[18]O of foraminifera shells, and the abundance of climate-sensitive foraminifera indicate that during the last glaciation the North Atlantic was punctuated by iceberg discharge events potentially produced in response to changes in ice sheet dynamics.[16] The largest of these (Heinrich events) have a characteristic recurrence in the marine record on the order of 5,000 to 10,000 years. They are also associated with similar events of shorter-timescale variability described above (on the order of 1,000 to 3,000 years long, termed Dansgaard/Oeschger rapid climate change events) that correlate with the stadial/interstadial changes observed in ice core records from central Greenland (see Figure 6.6).[17]

Evidence for the presence of millennial-scale climate fluctuations has been

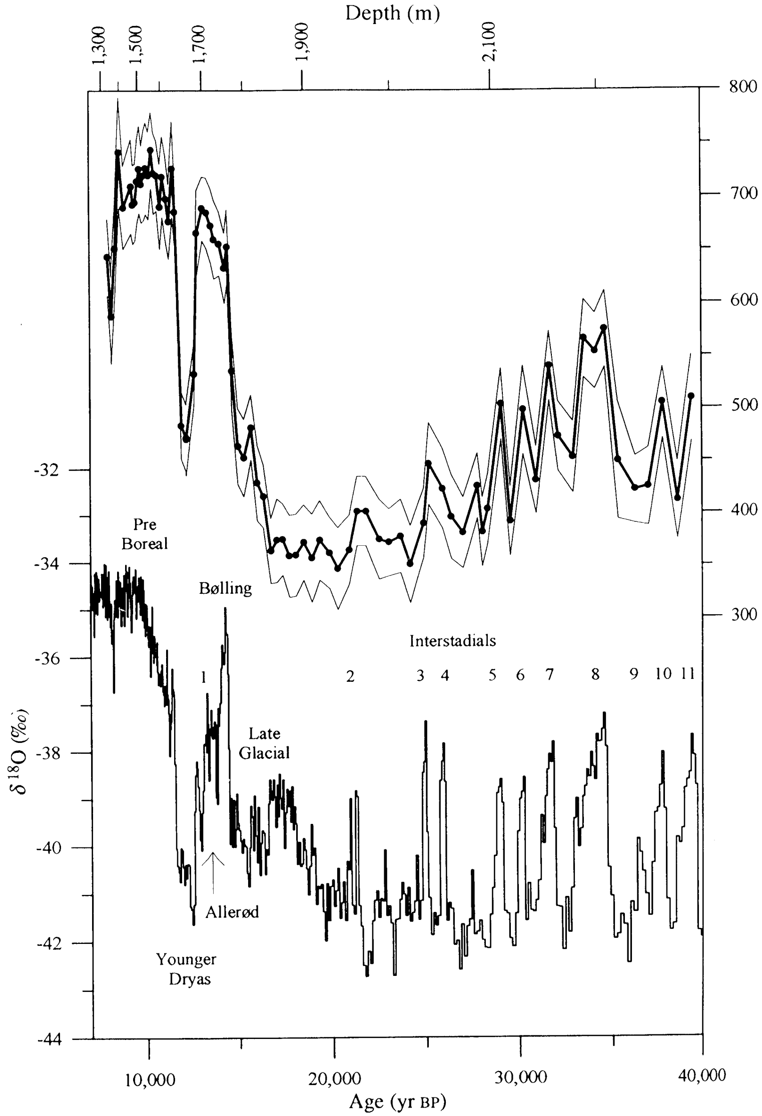

FIGURE 6.4 Top: GRIP ice core values for methane. The thick line runs through the mean concentration (black dots), and the two accompanying thin lines correspond to the experimental uncertainty (2 sigma). Bottom: Mean $\delta^{18}O$ record along 2.2-m sections of the core (Dansgaard et al., 1993; Johnsen et al., 1992). The significant climatic events are noted by name or suggested numbering (Dansgaard et al., 1993). The timescale applies to both records. The depth scale applies only to the CH_4 curve (top) because of the difference in age between trapped air and ice at a given depth. SOURCE: Chappellaz et al. (1993). Courtesy of Macmillan Magazines Ltd.

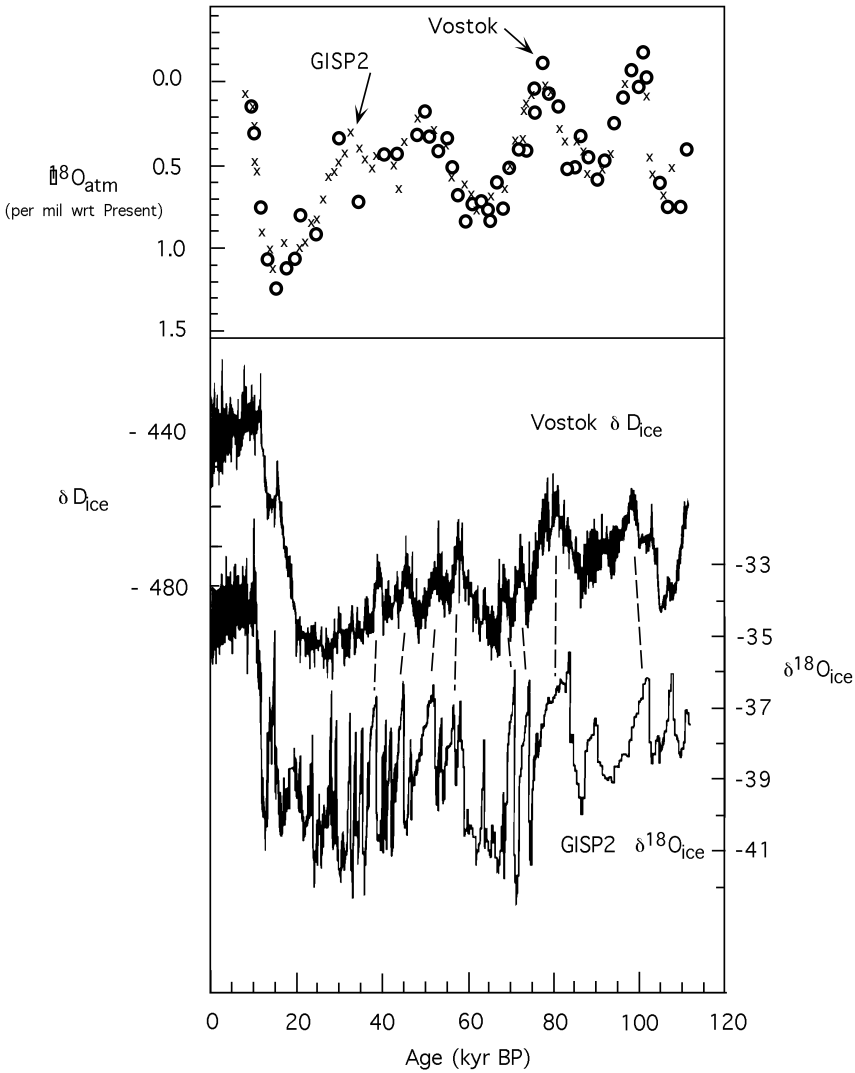

FIGURE 6.5 Greenland (GISP2) and Antarctic (Vostok) climate records covering the last glacial/interglacial cycle. Top: Plot shows the close correlation between GISP2 and Vostok $\delta^{18}O$ of O_2 in air in these ice cores. Bottom: Curves show close correlation between two proxies for temperature, δD_{ice} (Vostok) and $\delta^{18}O$ (GISP2) in the ice. SOURCE: Adapted from Bender et al. (1994). Courtesy of Macmillan Magazines Ltd.

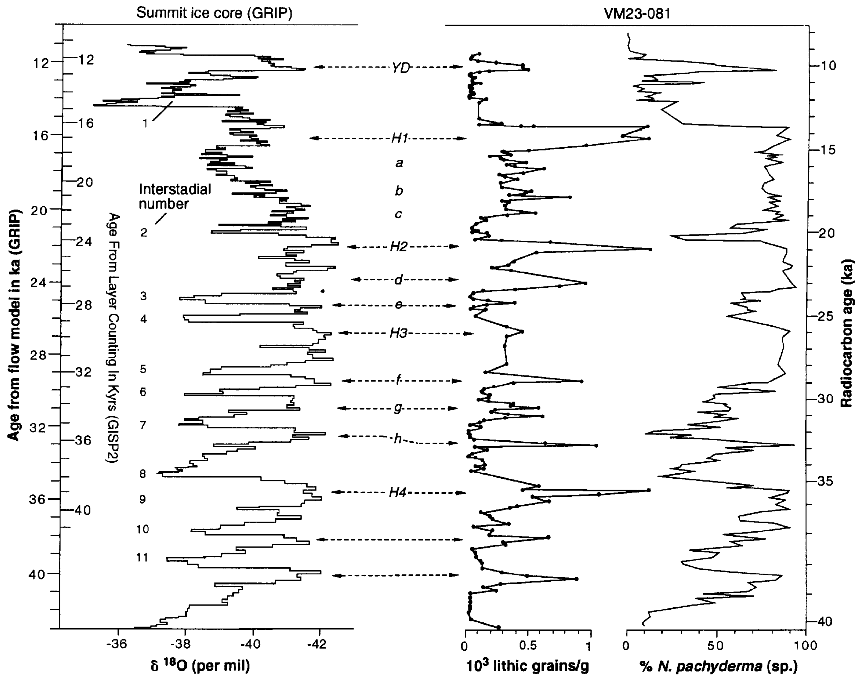

FIGURE 6.6 Comparison of the $\delta^{18}O$ record and age model for the GRIP ice core, Summit, Greenland (Dansgaard et al., 1993), with measurements of lithic concentrations and percentages of the planktonic foraminifera Neogloboquardrina pachyderma (left coiling), a proxy for surface water temperatures, in WM23-81 (Bond et al., 1993). That foraminifera today lives in waters <10°C and comprises about 95 percent of the fauna at summer temperatures of less than 5°C. Age model for the marine record is from Bond et al. (1992, 1993). Cycles between the Heinrich events are given letters to aid their description in the text. A good match exists between the lithic concentration cycles and the temperature cycles in the ice core; the match of the lithic cycles to the ocean surface temperatures, however, is much poorer. The GISP2 timescale derived from layer counting to 41,000 years is included for comparison with the GRIP timescale and the ^{14}C timescale. The GISP2 timescale was transferred into the GRIP record at the sharp interstadial boundaries, which are precisely located in both ice core records (Dansgaard et al., 1993; Mayewski et al., 1994), and then ages were interpolated between these boundaries. The progressive difference in ages, reaching about 10 percent at 40,000 calendar years ago, is consistent with the error estimated for ice core dating. SOURCE: Bond and Lotti (1995). Courtesy of the American Association for the Advancement of Science.

extended outside the North Atlantic and polar regions. Marine cores from the Santa Barbara basin reveal highly sensitive perturbations in the ocean circulation patterns of the East Pacific region[18] and ice-rafted debris events in the North Pacific that correlate with the Greenland ice core records. Abrupt changes in atmospheric circulation patterns and precipitation regime also are recorded over eastern Asia in a thick sequence of wind-deposited loess from central China.[19] Records of alpine glacier fluctuations, mountain snowlines, and paleovegetation in the Andes reveal climate fluctuations that are similar in regularity to events in the Greenland ice cores.[20]

While the exact phasing of rapid climate change events from region to region is still being examined, new advances in age-dating correlation techniques have provided insight into the bipolar phasing of major climate events close to the last glacial maximum. Measurements of the $d^{18}O$ of atmospheric O_2 from the Byrd and Vostok ice cores in Antarctica and the GISP2 ice core suggest that the transition from glacial maximum to deglaciation began in Antarctica approximately 3,000 years before the onset of warming in Greenland.[21] This view creates a more complex event phasing than that suggested by previous correlations of marine, coral reef, and ice extent records, which suggested that during the last termination nearly synchronous temperature changes affected ice masses from the poles to the equator.[22]

New advances in paleoclimate reconstruction also come from the tropics. For example, a 30,000-year-long paleotemperature record from lowland Brazil, based on noble gas concentrations in groundwater[23] and an Andean ice core[24] suggests a cooling of 5 to 8 degress, contrasted with earlier estimates from marine cores that limit cooling to >3 degrees.[25] Implications of this change in temperature to the hydrological cycle and consequently to climate are intriguing.[26] These new findings have stimulated examination of other tropical paleoclimate records and renewed investigations into climate forcing that is tied to changes in the tropics.

Causal mechanisms for glacial-age climate fluctuations appear to be complex, and phasing of these events is not understood from region to region. However, evidence for the identification of regularity in the timing of some climate events is building. Studies ranging from the North Atlantic (GISP2) to the subtropics demonstrate 1,450- to 1,800-year periodicities for rapid climate change events.[27] In addition, the cumulative effect of multiple climate forcings can now be demonstrated. As an example, ~90 percent of the variance in the GISP2 paleoatmospheric circulation series is related to insolation changes induced by the Earth's orbital cycles, which operate in concert with faster periodic climate forcings such as changes in ice sheet dynamics, thermohaline ocean circulation, and solar variability (see Figure 6.7).[28] Additional climate forcing mechanisms are, undoubtedly, also involved, such as changes in CO_2, CH_4, water vapor, volcanism, biogenic source cloud condensation nuclei, and dusts.

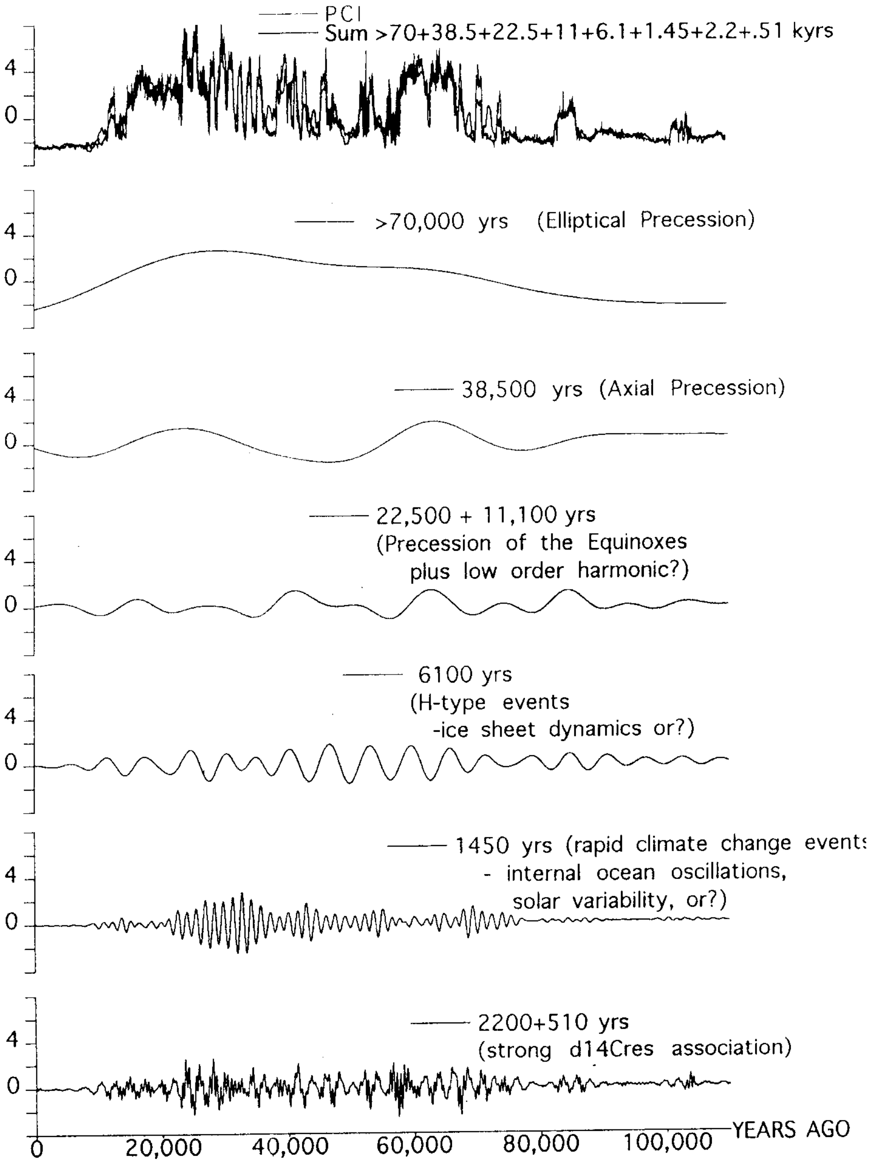

FIGURE 6.7 Top curve: [NRC9] The PCI (Polar Circulation Index) is a time series describing the dynamics (i.e., increase and decrease from mean values) of the well-mixed atmosphere represented by the dominant EOF of the major ions in the GISP2 ice core (Mayewski et al., 1994). The PCI provides a relative measure of the average size and intensity of polar atmospheric circulation. In general terms PCI *(continued)*

The Holocene

Summary of Previous Work

One of the most important tasks for paleoclimatologists is improving our understanding of Holocene climate, for it is within the Holocene that the boundary conditions for modern natural climate variability can be identified and from which the relative importance of natural versus anthropogenic climate forcing can be assessed. Understanding modern climate and predicting future climate will require a detailed understanding of Holocene climate forcing and response.

Millennial-scale and finer Holocene climate fluctuations have been identified for more than two decades in a variety of Holocene records.[29] In general, however, Holocene climate variability is significantly more subdued in magnitude than that recorded during the last glaciation, and significantly less attention has been paid to this portion of the paleoclimate record.

New Developments

Environmental response to climate change since the last glacial maximum has been considerable. COHMAP and numerous smaller research efforts have characterized and modeled the effect of changes in land and sea ice extent, sea surface temperature, vegetation, and extent of arid regions during selected periods. Fossil pollen data keyed to the distribution of modern analogs have been used to develop paleovegetation maps for regions such as eastern North America (see Plate 6).[30] Pollen and tree ring data have been used to reconstruct the spatial variations of temperature and precipitation over northern North America for the past ~6000 years.[31]

Several primary conclusions can be drawn from paleovegetation reconstructions.[32] Climate change events of the magnitude captured in these studies result in

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values increase (e.g., more continental dusts and marine contributions) during colder portions of the record (stadials) and decrease during warmer periods (interstadials and interglacials; Mayewski et al., (1994)). The PCI is contrasted with the sum of the bandpass components (>99 percent significance) estimated from this series. The sum represents about 90 percent of the variance in the original PCI series. Lower curves: Major bandpass components derived from the PCI series, including those with periodicities close to elliptical precession, axial precession, precession of the equinoxes, lower-order harmonics of the preceding, and periodicities potentially related to ice sheet dynamics, internal ocean oscillations (including changes in thermohaline circulation), and solar variability. The 6,100-year bandpass component describes the timing of H (Heinrich events) and the 1,450-year bandpass component of the timing of the rapid climate change events (Dansgaard/Oeschger) events in the GISP2 record. SOURCE: Adapted from Mayewski et al. (1997). Courtesy of the American Geophysical Union.

dramatic changes in vegetation over regions. Even individual taxa respond sensitively to climate change, and vegetation produced under conditions that lack modern analogs may not be found under modern climate conditions. Some attempts have been made to simulate vegetation patterns that could exist in 2 x CO_2 eastern North America, utilizing general circulation models (GCMs) coupled with paleoclimate-vegetation distributions.[33]

Annually resolved continuous paleoclimate records from the GISP2 ice core demonstrate that Holocene climate is characterized by annual- to millennial-scale variability and that Holocene climate is significantly more complex than glacial-age climate.[34] Time series for the major ions dissolved in the atmosphere, utilized as tracers for major atmospheric circulation systems, reveal a strong association between expansions of northern hemisphere polar atmospheric circulation systems and a variety of discontinuous paleoclimate records that record worldwide coolings (see Figure 6.4).[35] These events have a quasi-periodicity of 2,600 years in phase with previously defined ~2,500- year variations in d^{14}C, suggesting perhaps a solar variability-climate connection.[36]

Complexities in Holocene climate are noted in a comparison of several environmental parameters recorded in the Summit, Greenland, ice cores. During major Holocene coolings recorded in the GISP2 paleoatmospheric circulation series (see Figure 6.8), the climate response system operated similarly to pre-Holocene cooling events (Figure 6.3). Namely, cooler temperatures (more negative stable isotopes), reduced methane, reduced accumulation rate, and intensification of polar atmospheric circulation (expanded polar circulation index) all vary, in general, together. However, the coherence between these variables weakens as the events get younger and is particularly poor during the periods between events, suggesting increased regionalization of climate from early to late Holocene. This progressive regionalization of climate may be the manifestation of the varying influence of a variety of climate-forcing mechanisms, such as changes in total and season to season insolation, ice sheet and sea ice extent, solar variability, and volcanism.[37]

Several paleoclimate records document specific periods of climate reorganization. For example, African lake level records, developed in 1990,[38] suggest that a major period of ocean-atmosphere reorganization occurred between some 7,000 to 8,000 years ago. A similarly timed reorganization in climate has recently been documented by comparing records from tropical Africa with those from Greenland and Antarctica.[39] Other lake level records from Africa plus Dead Sea records suggest that both the tropics and the midlatitudes experienced a series of major changes in hydrological balance.[40]

Analysis of Arabian Sea sediment records spanning the past 24,000 years reveals that the response of the southwest monsoon over this region to long-term changes in insolation occurred in several distinct events of less than 300-year duration between 14,300 and 7,300 ^{14}C years ago.[41] Arabian Sea sediment records also document changes in the strength and frequency of the Indian monsoon (see Figure 6.9), confirming earlier reports that the monsoon strengthened in stages

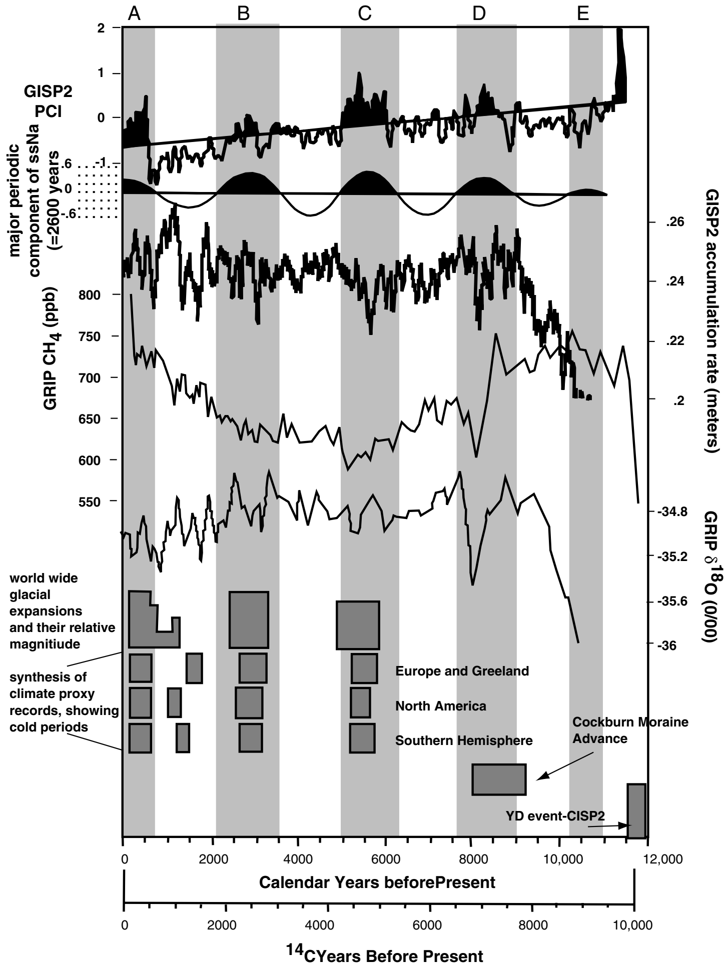

FIGURE 6.8 From top to bottom: GISP2 annually dated Holocene EOF1, a proxy for northern hemisphere polar cell intensity (PCI; described in Figure 6.8) smoothed with a robust spline (equivalent to a 100-year smooth)) with a quasi-2,600-year periodicity (O'Brien et al., 1996); GISP2 accumulation rate (Meese et al., 1994a,b); GRIP methane (Blunier et al., 1995); GRIP δ^{18}O record (Dansgaard et al., 1993); worldwide glacial expansions and their relative magnitude (Denton and Karlen, 1973); synthesis of various climate proxy records from Europe, Greenland, North America, and the southern hemisphere showing cold periods (Harvey, 1980); the Cockburn Stade (Andrews and Ives, 1972; Alley et al., 1997); and the Younger Dryas event (Alley et al., 1993; Mayewski et al., 1993). Letters specify major cold periods with A equal to the Little Ice Age. Courtesy of the American Association for the Advancement of Science, Macmillan Magazines Ltd., the University of Oulu, Geological Society of America, and Academic Press.

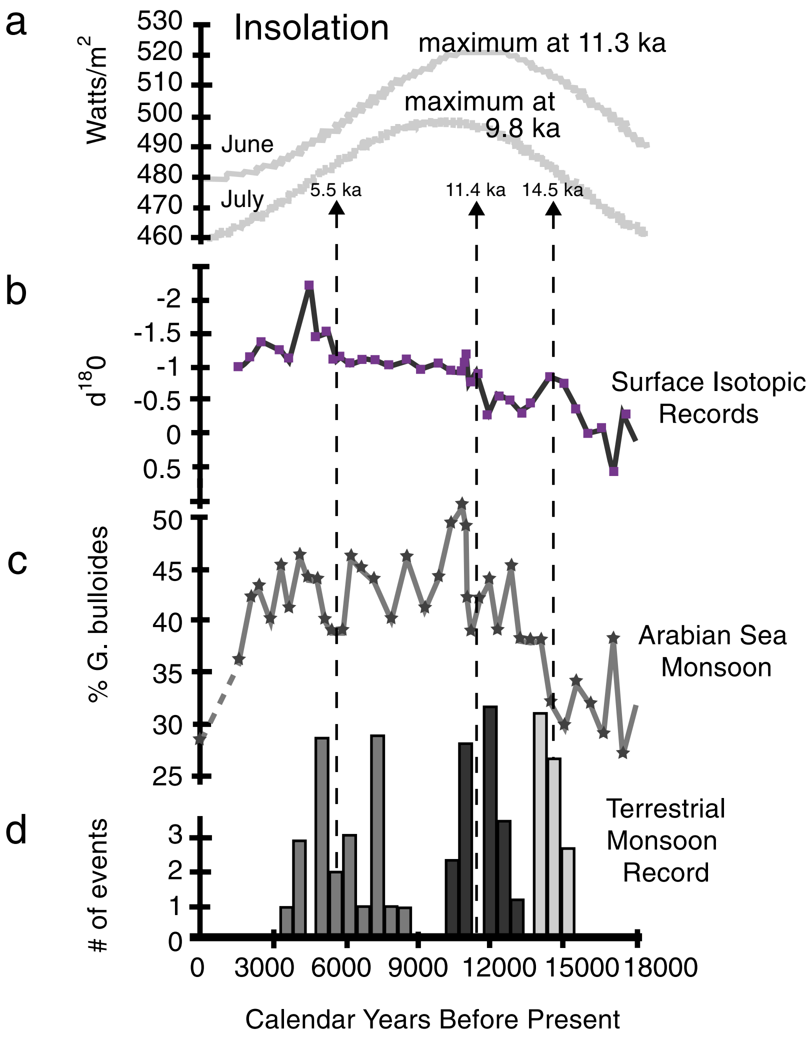

FIGURE 6.9 Summary figure illustrating the hypothesized insolation forcing and the lagged response of post-glacial southwest Indian monsoon intensification: (a) June and July insolation for 40°N, (b) RC27-23 surface isotopic record, (c) RC27-23 G. bulloides abundance (proxy for monsoon strength), and (d) histograms of abrupt monsoon-strength increases and decreases at sites across East Africa and southwestern Asia. Mid-Holocene decreases in monsoon strength appear to have been more time transgressive than the earlier abrupt increases and also more in phase with insolation forcing. The figure shows the timing of the first abrupt increase in monsoon strength (mean, 11,400 years), and the date at which the period of maximum monsoon strength apparently ended at each site (mean 5,500 years). Note that the period of maximum monsoon strength (at 11,000 to 5,000 years) lags peak insolation (at 14,000 to 8,000 years). SOURCE: Adapted from Overpeck et al. (1996). Courtesy of Springer-Verlag.

over the deglaciation.[42] The former study also identified a 3,000-year lag between monsoon intensity and insolation that lasted from about 9,500 to 5,500 years ago. By the end of this period, when northern hemisphere glacial boundary conditions had disappeared, monsoon behavior responded more linearly to insolation. Further significant centennial-scale decreases in monsoon intensity occurred prior to ~6,000 years ago, when monsoon strength was enhanced relative to the present. Since abrupt changes in Arabian Sea sediment monsoon records occurred when northern hemisphere summers were significantly warmer than present,[43] some researchers have speculated that future greenhouse-warmed summers[44] may offer "surprises" in monsoon behavior.

Major reorganizations in Holocene climate plus finer-scale climate fluctuations such as abrupt shifts in drought and flood frequency may be explained by a combination of climate forcings.[45] For the Holocene such forcings may include (1) changes in thermohaline circulation; (2) changes in insolation, notably precession that may generate long-period El Niño-type reorganizations in moisture and temperature and changes in marine and land ice cover; (3) changes in solar output; and (4) changes in the concentrations of volcanic aerosols and dusts.[46] A variety of paleorecords are available to test the impact of these forcing mechanisms, including, for example, potential proxies for solar variability derived from $d^{14}C$ series in tree rings and ^{10}Be series from ice cores, CO_2 from ice cores, CH_4 from ice cores, and volcanic sulfate from ice cores.[47]

The Late Holocene (~2,000 years ago to present)

Summary of Previous Work

Although the exact timing and geographic distribution of Holocene climate change events are complex, the past 1,000 to 2,000 years offer important opportunities for unraveling the decadal- to centennial-scale and finer climate variability that influences modern climate. There is general agreement that glaciers around the world expanded during at least parts of the thirteenth through the nineteenth centuries, a period called the Little Ice Age (LIA), and that warming occurred for several centuries prior to this period,[48] at least in some regions, during what is controversially called the Medieval Warm Period (MWP).

Similarities in decadal- to centennial-scale variability over the past 1,000 years are observed in a variety of paleoclimate records from, for example, China (e.g., temperature, drought, rain frequency, dust events), although differences in the timing of peak cooling differ by region.[49] Furthermore, broad similarities exist between the Chinese records and records covering a wide geographic range.

New Developments

Although spatially and temporally incomplete at present, paleoclimate records provide unique environmental reconstructions for the most recent millennia. The

LIA appears to play an important role in understanding modern climate. Based on the GISP2 atmospheric circulation record (see Figure 6.8), the LIA had the most abrupt onset (AD 1400 to1420) of any of the Holocene rapid climate change events.[50] This extends findings from a 1,500-year-long ice core record in the Andes which suggests that entrance into and out of the LIA was abrupt.[51]

Previous research summarized by Lamb (1995) demonstrates changes in climate such as increased severity of winter storms and sea ice extent, plus accompanying changes in food harvests during the LIA and contrasting milder conditions during the MWP. Recently developed marine sediment records from the Sargasso Sea[52] suggest that sea surface temperatures in the Bermuda Rise region were ~1 degree cooler than today ~400 years ago (during the LIA) and ~1,700 years ago, and ~1 degree warmer than today 1,000 years ago (during the MWP). On the basis of this work,[53] it is suggested that part of the general climate warming of the past few decades[54] could be natural. During the MWP extreme and persistent drought characterized such regions as California and Patagonia,[55] implying potential "surprises" during warmer-than-present climates.

Composite time series for El Niño recurrence (see Figure 6.10) suggest that fewer such events occurred during the MWP than during colder intervals prior to and following this time.[56] Studies conducted over only the past 500 years, which do not include the LIA/MWP transition, suggest that El Niño recurrence rate is stationary over the long term but that strong El Niño events are nonstationary over centennial scales.[57]

Analysis of records covering the past 500 years suggests the presence of persistent natural interdecadal and century-scale climate oscillations. A compilation of paleoclimate records representative of the past 400 years of circum-Arctic climate variability indicates that the highest temperatures over this period have occurred since 1840, demonstrating the role of natural climate variability and, as of 1920, the added climate influence of atmospheric trace gases.[58] Multidecadal modes and step-function changes in precipitation, temperature, and wind regimes have been identified in a number of regions, ranging from the Intertropical Convergence Zone (ITCZ) to both northern and southern midlatitudes. Recent attempts to match decadal-scale climate change events from region to region do not, however, necessarily reveal synchronous behavior over the past few centuries.[59]

Although their relative importance is still debated, several mechanisms have been proposed for the natural changes in climate of the past millennium, including changes in solar output, an increase in volcanic aerosols during specific periods, an increase in long-term average atmospheric aerosol loading, variations in thermohaline circulation, and changes in greenhouse gases.[60]

The paleoclimate record offers the potential to deconvolve the region-to-region climate variability that characterizes the Holocene on millennial to decadal plus finer timescales. Although few such records are available at present, these records offer immense potential (see Box 6.1).

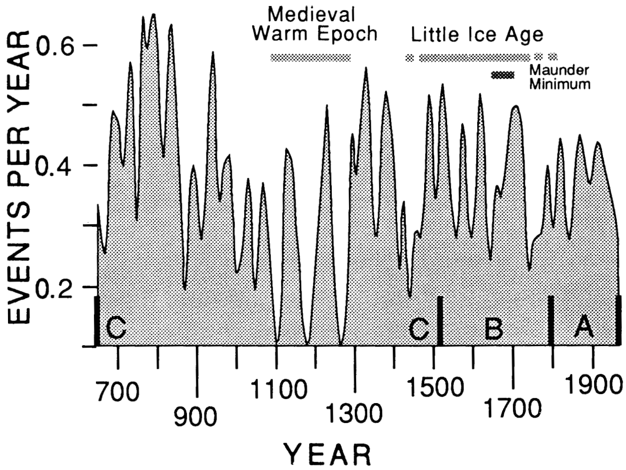

FIGURE 6.10 Composite time series for recurrence of El Niño events since AD 622. Linearly weighted 19-year running mean. Data from Quinn et al. (1987) and Quinn (1992). Segment C (Nile), 622 to 1525; segment B, 1525 to 1800; segment A, 1800 to 1984. SOURCE: Anderson (1992). Courtesy of Cambridge University Press.

Climate-Vegetation Interaction

Summary of Previous Work

Early climate studies of modern tropical deforestation[61] have focused attention on the importance of climate-vegetation interactions in governing the surface energy and moisture fluxes and hence the importance of climate-vegetation interactions. More recently,[62] it was proposed that boreal forests, in addition to tropical vegetation, have an important climatic effect. A climate model was used to demonstrate that expansion of the boreal forest, associated with greenhouse warming, would enhance this warming through albedo feedback because trees mask the high reflectance of the high-latitude snow cover. In particular, tree cover, even with underlying snow cover, promotes springtime warming. These contributions introduce the potential of climate-vegetation feedbacks to substantially modify the sensitivity of the Earth's climate to a large number of different forcing factors. Earth history enables an assessment of the importance of vegetation-climate feedbacks for a diverse number of forcing factors (carbon dioxide, solar variations, orbital variations, sea level, changes in continental geometry). But most importantly, the combination of knowledge about the nature of the forcing factors, the paleobotanical record of vegetation distribution, and the record of temperatures presents a unique opportunity to critically assess climate-biosphere sensitivity.

BOX 6.1 Available Climate Records of the Past Millennium

Climate Patterns

Temperature and Drought. Tree ring studies offer the greatest potential for developing broad spatial arrays of relatively recent, well-dated proxies for temperature and drought. Filtered tree ring series from, for example, Tasmania clearly reveal interdecadal patterns in temperature (see Figure 6.11).[63] In addition, 250- to 300-year reconstructions of spring/summer temperatures are available for western North America and western Europe,[64] winter precipitation and annual temperature in western North America,[65] and drought in the conterminous United States.[66]

ENSO. There are proxy ENSO time series available from a variety of records, including, for example, historical records, tropical corals, tropical ice cores, and polar ice cores.[67] Of particular note are the newly emerging annually resolved coral records that through calibration with the instrumental record provide proxies for zonal winds and precipitation (see Figure 6.12).[68]

North Atlantic Oscillation (NAO). GISP2/GRIP d^{18}O series have significant correlations with the NAO series.[69]

Sea Ice. Proxies for sea ice variability are available from Antarctic and Arctic ice cores.[70]

Climate Forcing

CO_2. Detailed records of naturally and anthropogenically induced changes in atmospheric CO_2 from an Antarctic ice core (see Figure 6.13) reveal preindustrial carbon dioxide mixing ratios in the range of 275 to 284 ppm, over the time period of the LIA and MWP.[71]

Sulfate and Nitrate. High-resolution time series for sulfate and nitrate from a south Greenland ice core, covering the past two centuries, demonstrate the difference between natural pre-1900 levels of these two acidic species versus post-1900 values (see Figure 6.14).[72] In the preanthropogenic atmosphere over Greenland, nitrate levels were approximately two times the sulfate levels. Increased levels of sulfate during the anthropogenic era mask volcanic sulfate levels, indicating the large rise over natural background during this period. Volcanic events recorded in Greenland ice core sulfate series correlate with annual changes in atmospheric temperature, providing evidence for sulfate aerosol shielding.[73]

Solar Variability. d^{14}C series from tree rings and ^{10}Be series from a Greenland ice core provide potential proxies for solar variability.[74] ^{10}Be series vary inversely with sunspot activity, and ^{10}Be production varies inversely with temperature (see Figure 6.15).[75]

New Developments

Recent applications of biome and simple vegetation-climate models coupled with GCMs and applied to the study of Earth history have resulted in a number of

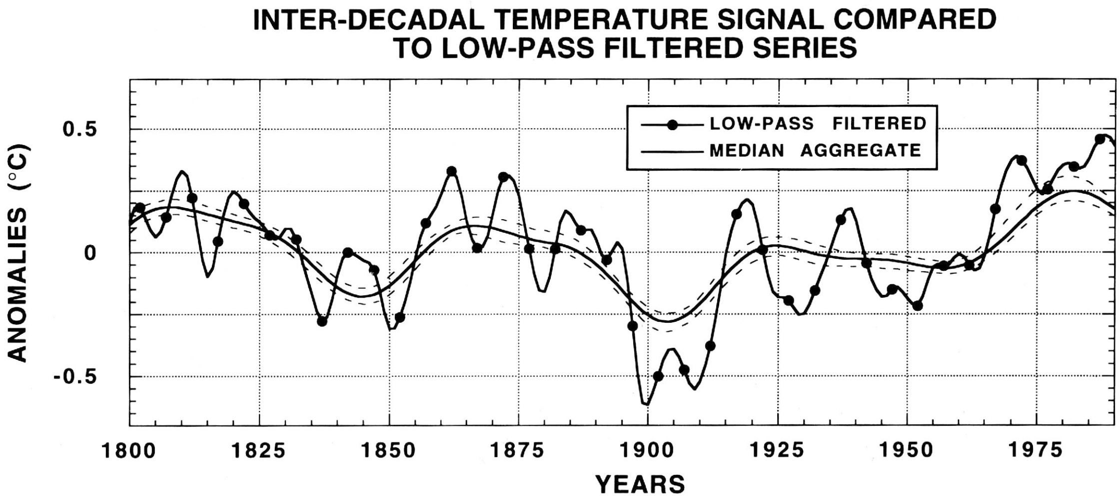

FIGURE 6.11 The median aggregate waveform since AD 1800 with its approximate 95 percent confidence limits compared to the low-pass filtered series developed from Tasmanian tree ring series. The aggregate appears to explain much of the interdecadal warming in the reconstruction since AD 1965. SOURCE: Cook et al. (1996a, b). Courtesy of Springer-Verlag.

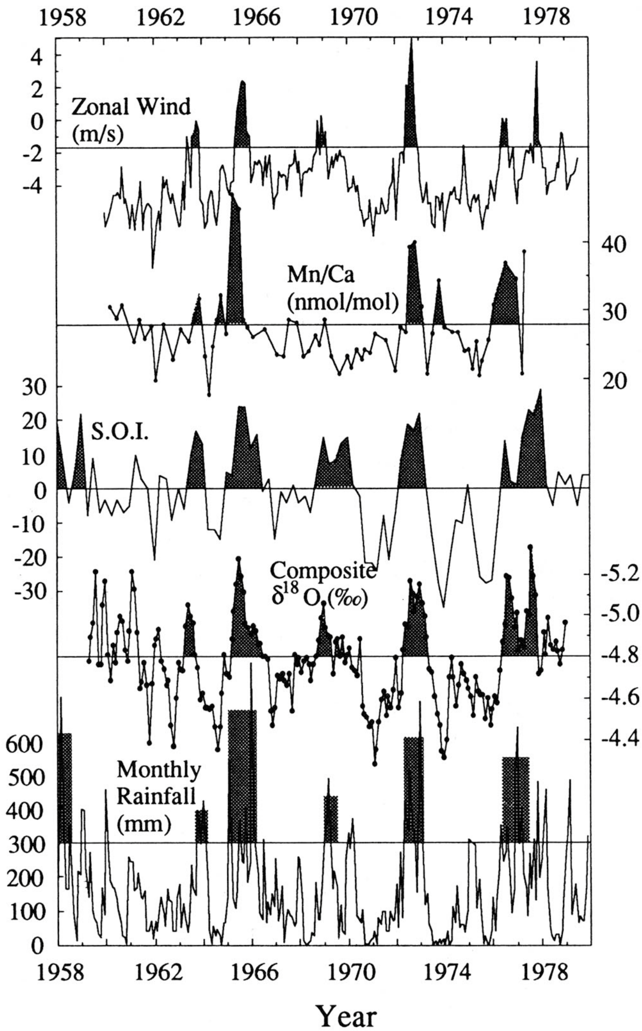

FIGURE 6.12 Instrumental and coral records of environmental conditions at Tarawa Atoll. From top: zonal winds, coral Mn/Ca (Shen et al., 1992), the Southern Oscillation Index (SOI; Wright, 1989); composite coral $\delta^{18}O$ (plotted reverse; Cole and Fairbanks, 1990) and monthly rainfall (from Monthly Climatic Data for World and New Zealand Meteorological Service). Shaded periods reflect ENSO warm-phase conditions as noted by Quinn et al. (1978, 1987), which involve the weakening and reversal of the trade winds and dramatically increased rainfall at this site. SOURCE: Cole et al. (1992). Courtesy of Cambridge University Press.

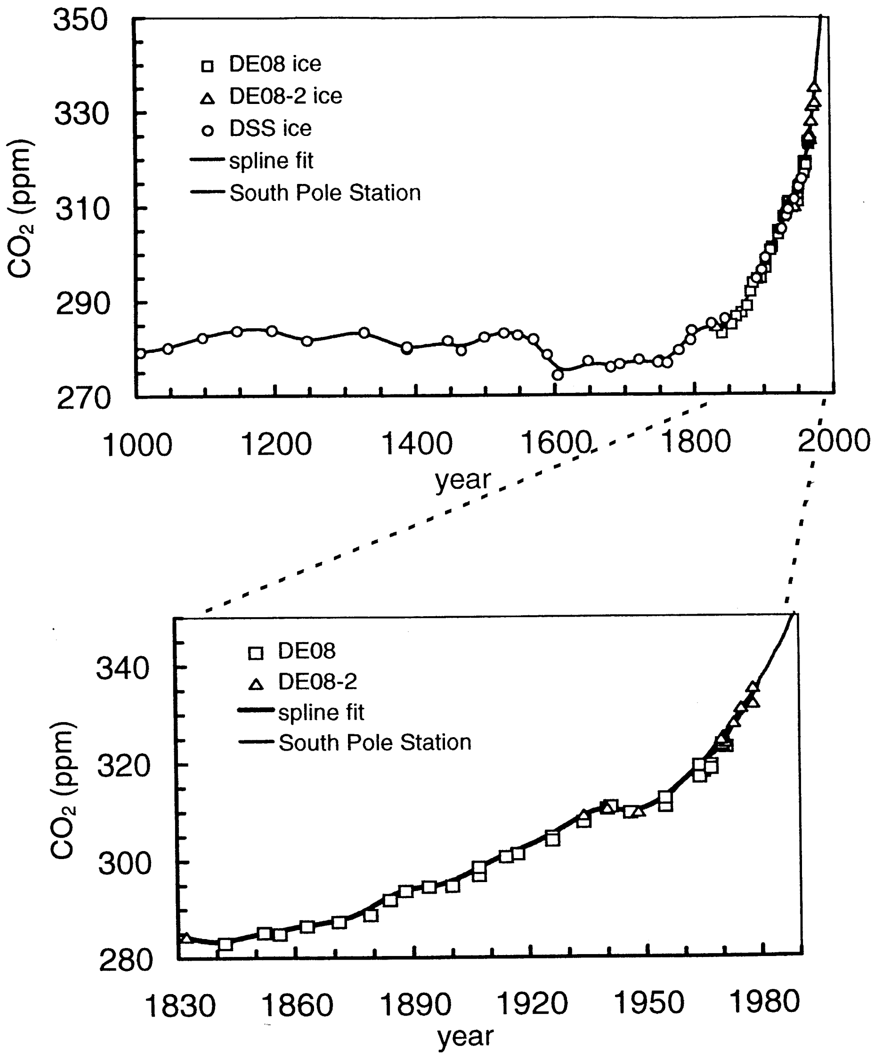

FIGURE 6.13 Top: CO_2 mixing ratios from the DEO8, DEO8-2, and DSS ice cores, Law Dome, East Antarctica, and modern South Pole atmospheric record (Keeling, 1991). Bottom: CO_2 mixing ratios since early last century from DEO8 and DEO8-2 Law Dome ice cores and the South Pole record (Keeling, 1991). The thick line is a smoothing spline fit to the DEO8 and DEO8-2 data. The degree of smoothing has been set such that an attenuation of 50 percent occurs for CO_2 variations of 20 years' duration. Such smoothing was found to best attenuate the shorter-frequency variations that, because of the averaging effect of the air enclosure process, are unlikely to be real atmospheric features and are assumed to be measurement errors. SOURCE: Etheridge et al. (1996). Courtesy of the American Geophysical Union.

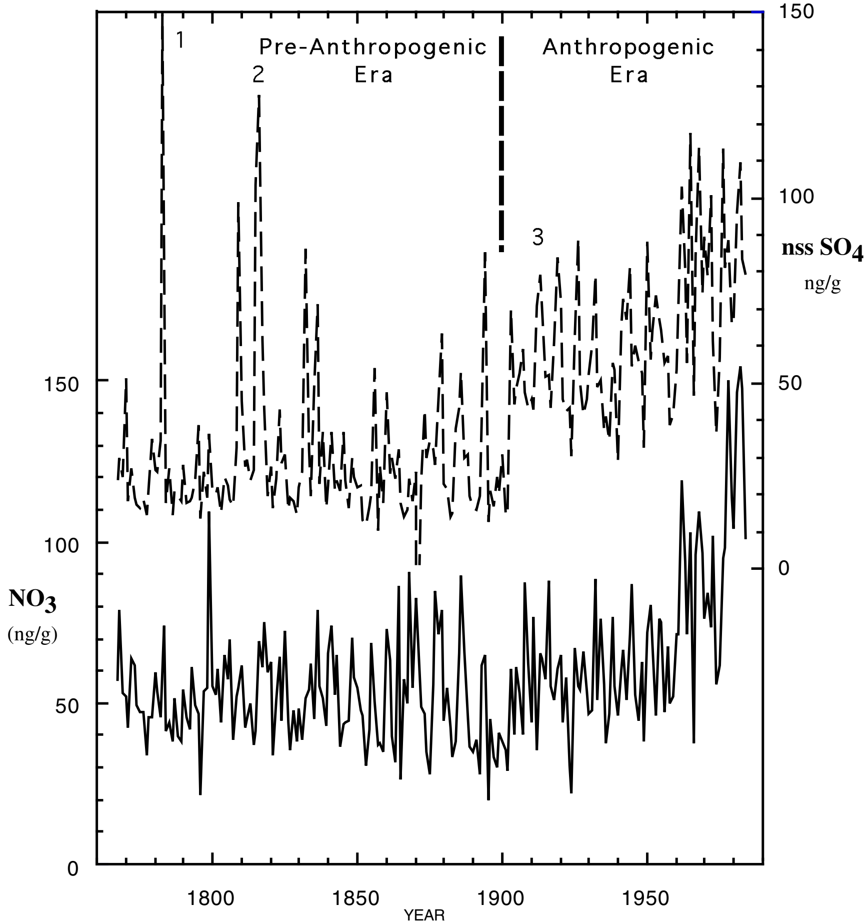

FIGURE 6.14 Time series of the nonseasalt sulfate (nss; dashed line) and nitrate (solid line) concentrations at ice core site 20D, southern Greenland. Data have been smoothed (using a gaussian function) to periods of one to two years from the original five to eight samples per year to remove seasonal signals. Examples of volcanic events recorded in nss sulfate spikes are (1) Laki (1783), (2) Tambora (1815), and (3) Katmai (1912). SOURCE: Adapted from Mayewski et al. (1990). Courtesy of Macmillan Magazines Ltd.

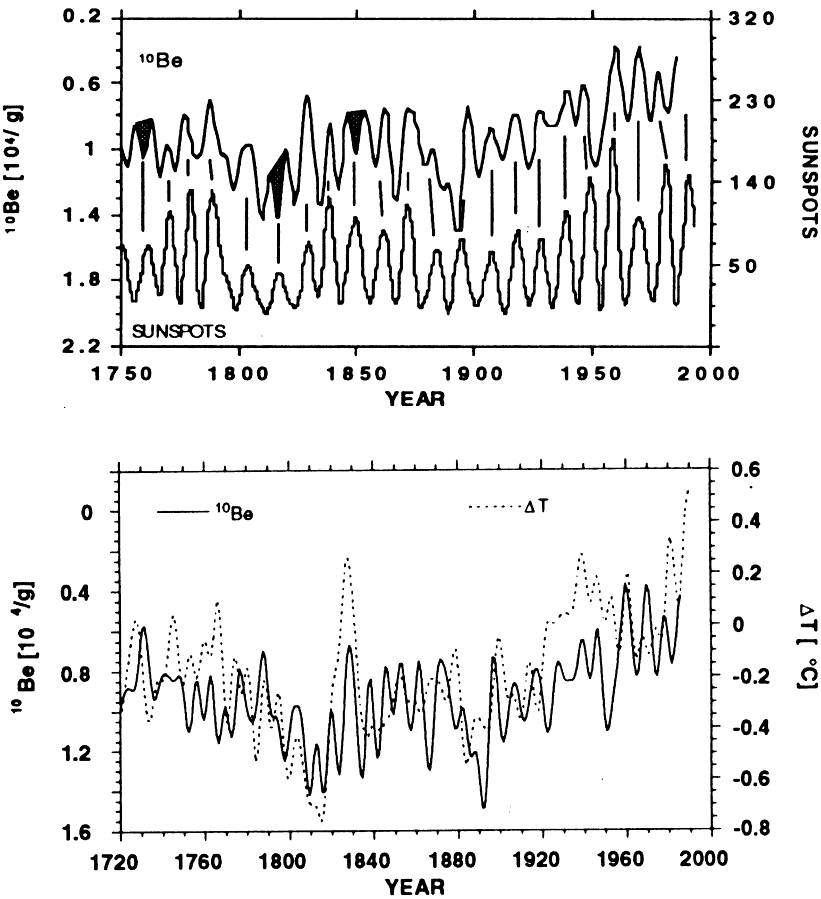

FIGURE 6.15 Top: ^{10}Be measurements derived from the Dye 3 ice core vary inversely with sunspot activity. Bottom: Observed inverse relationship of ^{10}Be production and temperature. SOURCE: Beer et al. (1994). Courtesy of Cambridge University Press.

remarkable conclusions. Foley et al. (1994) have shown that mid-Holocene warming associated with changes in the Earth's orbit was enhanced, particularly in springtime, by an associated poleward expansion of the boreal forests. Gallimore and Kutzbach (1996) have suggested that the onset of the last glaciation was accentuated by the observed equatorward retreat of the boreal forests associated with the cooling. Deriving sufficient climate model sensitivity from changes in the Earth's orbit to produce the observed glacial-interglacial cycles has been a long-standing problem. Evidently, climate-vegetation feedbacks are a likely candidate to solve this problem, at least partially. In a similar vein, Dutton and Barron (1996, 1997) have suggested that the development of widespread grasses in the Miocene and the retreat of the boreal forests observed to be associated with the development of widespread ice caps could have substantially enhanced the Late Cenozoic cooling. They suggest that both biological innovation (development of a new widespread flora) and climate-vegetation feedbacks (e.g., climate-boreal forest-albedo relationship) may play an important role in governing climate.

More than 20 parameterizations for the land surface are now included in the World Climate Research Programme's Project for Intercomparison of Land Surface Parameterization Schemes.[76] Intercomparison of these parameterizations provides a strong foundation for understanding the role of vegetation in governing moisture and energy fluxes. With this foundation we can expect a much greater understanding of the importance of vegetation character and distribution in governing climate.

A primary objective for future research must be to include dynamic vegetation, which evolves with climate change and allows explicit incorporation of climate-vegetation feedbacks. A number of different vegetation models are available now or are under development. Biome models, in which vegetation functional form and species distribution are governed by key climatic variables, provide the foundation for other models.[77] The life-form model (EVE—Equilibrium Vegetation Ecology model)[78] provides an alternative, in which the net phenology and physical attributes of the vegetation community are determined for each climate model grid point based on the climatic relationships of 110 life forms. Again, pathfinder studies guide research on the application of these models to Earth history. A prescribed change in climate to assess vegetation change has been applied using the Prentice biome model.[79] A "dynamic" Holdridge-type vegetation scheme[80] has been used to assess climate-vegetation change for a transient doubled carbon dioxide experiment. Again, each of these pioneering studies lacks a capability to verify the results based on climates very different from the present day. In contrast, Earth history presents a considerable record of vegetation character and distribution. Extensive published summaries of the vegetation distribution and history for the Last Glacial Maximum have been provided.[81] Global Tertiary (past 65 million years) vegetation distribution maps and recent updates are available.[82] Extensive references are given for the Eocene climate,[83] and both phytogeographic maps and extensive references for the mid-Cretaceous are available.[84]

However, actual applications of climate-vegetation models for past climates have been limited. The ability of three different biome models to predict present-day vegetation distribution[85] has been assessed using the GENESIS[86] GCM; these biome models were then applied to the simulation of the Younger Dryas and the Eocene. In these cases the vegetation was not coupled to the GCM but rather was calculated "off-line" after the GCM produced a climate simulation.

Hence, these models predict a change in vegetation that can be compared to observations but do not include vegetation-climate interaction. EVE was utilized to perform a dynamically coupled experiment to incorporate the role of a changing vegetation in assessing climate sensitivity.[87] Results for the Late Cretaceous suggest that vegetation-climate feedbacks could be a contributing explanation of Cretaceous polar warmth.

The application of ecological models, coupled with climate models, is obviously in its infancy. However, efforts to date have several implications. First, climate-vegetation interaction has the potential to substantially alter the sensitivity of climate models. Second, an intercomparison of several different land-atmosphere interaction parameterizations and the spectrum of ecological models is essential. Third, vegetation characteristics and distributions from Earth history have considerable potential as a means of assessing the importance of climate-vegetation feedbacks and in validating coupled climate-vegetation simulations. These data are a unique opportunity to investigate a critical aspect of global change.

Climate-vegetation interactions extend beyond the effects associated with the expansion and contraction of specific biomes due to warming or cooling. For example, carbon dioxide concentrations are evidently correlated with stomatal parameters (frequency and size) on the leaves of land plants.[88] It has also been suggested that C4 plants are adapted to conditions of water and CO_2 stress and that their widespread expansion 5 million to 7 million years ago was related to lower carbon dioxide levels.[89] These vegetation responses are related specifically to the nature of the climate forcing and introduce the potential of utilizing the floral record with proxies of past atmospheric carbon dioxide levels to examine plant responses.

Warm Climates

Summary of Previous Work

Earth history is characterized by time periods in which the climate was significantly cooler and significantly warmer than the present day. Much of the past 150 million years has been substantially warmer than the present day, although a long-term climatic cooling has dominated over the past 60 million years. The extreme warm climates of the past provide an unique set of case studies of global change. They challenge our ability to describe, model, and understand how various elements of the Earth's climate operate and interact. These time periods also provide a critical test of the models used to predict the global climate response to increases in atmospheric greenhouse gases. Although a wide variety of climatic forcing factors have operated over Earth history, variations in atmospheric carbon dioxide concentrations are now linked to the record of climate change on almost every timescale, from abrupt events, to glacial to interglacial cycles, to the Cenozoic global cooling trend, to the major glaciations, and to the climate of the Archean (early Earth). Substantial evidence is available that links many of the extreme warm periods of the past 100 million years to higher carbon dioxide levels.[90] The most recent occurrences of these climatic extremes tend to be the best documented, with sufficient information to provide major challenges to climate models.

There is abundant evidence for global warmth during the mid-Cretaceous (about 100 millions years ago). There is no convincing evidence for permanent polar ice during this time. Arctic Ocean cores recover abundant phytoplankton,[91] suggesting at least a seasonally ice-free Arctic. More importantly, more than 400 species of land plants have been recorded from land well within the Arctic Circle.[92] Vegetation analysis[93] indicates mean annual temperatures from the North Slope of Alaska to be 10 to 13 degrees. Cretaceous deep-water temperatures, derived from the oxygen isotopic composition of benthic foraminifera, are as warm as 15 to 17 degrees. Evidence from the Cretaceous tropics is more problematic, but evidently temperatures were similar to or somewhat warmer than the present day. Equator-to-pole surface temperature gradients were therefore substantially lower than at present, and the Cretaceous Earth was substantially warmer, perhaps at all latitudes. Continental geometries were substantially different from the present day, and carbon dioxide levels were two to eight times present-day values.[94]

The Eocene (approximately 40 million to 50 million years ago) was also substantially warmer than at present. Oxygen isotopic measurements suggest that the high-latitude oceans were quite warm (perhaps as much as 10 degees warmer than at present at 60 degees N), but the tropics were as much as 5 degrees cooler.[95] The interpretation of polar warmth is supported by abundant floral and faunal data.[96] The remains of ectotherms, like alligators, above the Arctic Circle have been used to suggest frostless winters in coastal regions above 70 degrees N. In addition, floral data from the Eocene continental interior, such as the presence of palms at the latitude of present-day Chicago, indicate very mild winters even in continental interiors.[97] The nature of the Eocene climate is also deduced from measurements of the size of aeolian dust transported through the atmosphere and deposited in the deep sea. Eocene grain sizes are substantially smaller, on a global basis, than earlier records or modern records. The Eocene record is also one of a substantially smaller equator-to-pole gradient, but in this case the poles are substantially warmer and the tropics cooler. This suggests a very different climate mode from the warm Cretaceous. Temperature gradients similar to the Eocene pattern are characteristic of much of the Cenozoic preceding the development of permanent ice caps on Antarctica. According to one report,[98] Eocene carbon dioxide levels may have been moderately higher than at present.

The Cretaceous and Cenozoic warm climates present a substantial challenge to climate models used to predict future climate change. They are the basis for exploring a number of different forcing factors and for determining the sensitivity of the climate system to these factors. Each provides an interesting and valuable opportunity to validate climate models and to assess the nature of climate change and climate sensitivity. If major discrepancies exist between model predictions and the geological record, this analysis will focus attention on areas of needed research.

New Developments

Past warm climates have become a focal point for climate model study. Two results from these studies are particularly interesting. First, modern atmospheric GCMs appear to be incapable of achieving the equator-to-pole temperature gradients for the Eocene or the Cretaceous, although with higher carbon dioxide concentrations they can achieve reasonable globally averaged surface temperatures. Second, the record suggests that the mid- to upper range of Intergovernmental Panel on Climate Change (IPCC) estimates of climate sensitivity to increases in carbon dioxide better fits the geological data.

The first challenge introduced by the record of past warm climates is the reduced equator-to-pole surface temperature gradients. A universal response of atmospheric GCMs to increases in carbon dioxide concentrations is a small increase in tropical temperatures and a greater sensitivity at higher latitudes. To achieve the polar warmth of the Cretaceous (e.g., by increasing atmospheric carbon dioxide levels and incorporating Cretaceous continental geometries), GCMs produce an overheated tropics.[99] The nature of the problem is even greater for the Eocene, as tropical temperatures are lower compared to the present day while high-latitude regions are considerably warmer.[100] If the sea surface temperature data are correctly interpreted, the solution must lie in a redistribution of energy. The choices are limited. Either the ocean-atmosphere system is capable of more efficient transport of energy poleward, cloud amounts and character change systematically with latitude in warmer climates, or the energy input to the Earth system is dramatically different. The latter point appears to be excluded based on celestial mechanics. A cloud hypothesis can be made to work but is difficult to justify. The more efficient energy transport idea also can be made to work but presents an enigma.

If the mechanisms of poleward heat transport are examined, there are few opportunities to promote increases in the efficiency of transport during conditions like that of the Eocene. With cooler tropics and warmer poles, both atmospheric sensible and latent heat transport should decline. The aeolian record described above, in fact, is evidence for a weaker atmospheric circulation. If the atmospheric circulation is weaker, the wind-driven ocean surface circulation should be weaker. The only apparent opportunity to increase poleward heat transport is through the deep thermohaline circulation of the ocean. The role of ocean heat transport changes in explaining climate change has become a topic of considerable interest.[101] One possibility is a reversal of the thermohaline circulation and the production of warm highly saline deep water in the evaporative subtropics as the dominant bottom water source in times of warm polar temperatures. The implications of such a reversal in circulation on the characteristics of the ocean are considerable. A number of studies[102] suggest that modest increases in ocean heat transport—on the order of one or two times the amount of heat transported by North Atlantic deep water—would be sufficient to explain much of the paleoclimatic data.

The conclusions from such studies are of considerable interest. These studies introduce the possibility that the role of the ocean under climatic conditions very different from the present day may be very different from the modern ocean. GCMs without coupled oceans may be unable to simulate climatic sensitivity or the distribution of temperatures over the surface to the Earth. Furthermore, the challenge is to incorporate an adequate thermohaline circulation into coupled ocean GCMs. What is clear is that modern atmospheric GCMs are incapable of reproducing the temperature gradients of much of the warm climate periods of the past 100 million years.

The geological record also can be utilized to calibrate model sensitivity to increases in carbon dioxide concentrations in the atmosphere.[103] For example, one study uses global, mean annual, equator-to-pole temperature gradients, ranges in atmospheric carbon dioxide, and assumptions about the nature of other forcing factors to suggest that the midrange of the IPCC estimates (1.5 to 4.5 degees) for a doubling of carbon dioxide is appropriate for much of the Earth's history.[104] It was further noted that the uncertainties in some of these factors probably mean that the paleoestimates of climate sensitivity to increases in atmospheric carbon dioxide have about the same error range as the IPCC estimates.[105] In more detailed studies using GCM results[106] the actual distribution of surface temperatures was the basis for comparing model simulation results for differing levels of carbon dioxide. The GCM that was used yielded a 2.75 degrees warming for a doubling of atmospheric carbon dioxide. With this model the upper level of carbon dioxide estimates from the Cretaceous based on a variety of geochemical estimates[107] was required to achieve Cretaceous warmth. This implies that either unknown forcing factors were operating during the period or that the middle to upper range of IPCC estimates of climate sensitivity is required to explain past climates.

Caution must be applied in using the Earth's history to assess climate sensitivity. There are simply too many potential errors, in the interpretations of the observations, in knowledge of the forcing factors involved, and in the veracity and capability of the climate models used. It is critical to focus on better proxy information at all timescales. However, it is interesting to note that in the more than 100 simulations of past climates with GCMs we are yet to see a simulation that did not underestimate the record from past climates, unless specific assumptions were made in order to achieve past climatic conditions. This statement applies to both past cold and past warm extremes. This aspect of paleoclimate simulations has been the basis for suggesting that past climates imply a climate sensitivity that is within or exceeds IPCC estimates.

A focus on past extremes in climate obviously presents a challenge to the climate models used to assess future climates. The record of past warm climates appears to be impossible to assess adequately without taking into account the potential role of the ocean in global change. Furthermore, these time periods are suggestive of a very different role for the oceans during warm climates. In fact, it may be inadequate to have a coupled ocean-atmosphere model if the ocean model does not have a credible thermohaline circulation. Importantly, this is just one example of a potential inadequacy of current climate models as illustrated by paleoclimate investigations. Other factors and model systems also may be important, such as incorporation of dynamic vegetation. Past climates also present an opportunity to assess the nature of climate sensitivity. This type of application is imperfect but appears to suggest that past climates will be very difficult to simulate if climate sensitivity to carbon dioxide increases is in the lower range of IPCC estimates.

KEY SCIENTIFIC QUESTIONS AND ISSUES

The key scientific questions facing paleoclimate researchers have been articulated in a series of international projects, including PAGES (Past Global Changes) of the International Geosphere-Biosphere Programme, CLIVAR (Climate Variability) of the World Climate Research Program, and GLOCHANT (Global Changes in the Antarctic) of the Scientific Committee on Antarctic Research. Through the integration of ice, ocean, and terrestrial paleorecords, these international efforts seek to develop a basis for understanding the characteristics of natural global environmental change, notably climate change. These paleodata are essential for assessing human influence on the global environment and for evaluating predictive climate models.

Several questions and issues have evolved as foci for the paleocommunity. These consensus views have been expressed in several documents[108] which form the basis for the specific scientific questions that follow.[b]

Focus on the Past 2,000 Years

Paleoclimate records demonstrate that Holocene climate has been by comparison with glacial climates both warm and relatively stable. Furthermore, it is within the confines of Holocene climate that modern civilization has emerged and prospered, which is suggestive of some relatively benign climate influence.

[b] Following internationally accepted PAGES guidelines, these issues are divided into two streams—the past 2,000 years and the past 250,000 years.

While correct in the context of glacial/interglacial cycles, annually resolved ice core records from central Greenland demonstrate increased complexity in climate through the Holocene—as, for example, cold climate feedbacks produced by the presence of ice sheets dissipated during the early Holocene. Moreover, detailed examination of these and other paleoclimate records suggests that subdued versions of glacial-age rapid climate change events regularly punctuated the Holocene and that major atmospheric phenomena such as ENSO and monsoons varied markedly in frequency and magnitude throughout the Holocene. In fact, closer examination of Holocene climate records reveals more variability than that typically observed in the instrumental records covering the past century. Paleoclimate reconstructions, while not generally as accurate as the instrumental record, can uncover information from times and regions not covered by the instrumental record, thus supplementing it.

The past 2,000 years of Holocene climate offer examples of climates both warmer than modern (the MWP) and colder (LIA). While these climate events do not serve as strict analogs for future warmer or colder climates because they predate the industrial era, they do offer important "climate opportunities." Furthermore, despite the fact that instrumental records are most commonly less than a century in length, abundant and relatively untapped records in the form of historical journals and natural archives (e.g., tree rings, ice cores, corals) are relatively abundant for this period. Embedded in these records is evidence of both climate response (e.g., changes in temperature, precipitation, circulation strength) and climate forcing (e.g., solar variability, biogenic emissions, volcanism).

The most recent major climate event of the Holocene—the Little Ice Age—was a period of regionally lowered temperatures, increased atmospheric circulation intensity, and significant decadal-scale variability. While Holocene climatic shifts larger than those of the LIA are recorded in several proxy records, the LIA appears to have started more abruptly (within several decades) than other Holocene climate change events. The significance of this climatic "surprise" is not fully understood.

Despite general agreement that temperatures characteristic of the LIA have not characterized the twentieth century, there is considerable debate over the timing and geographic extent of this event and little discussion of the other climate parameters (e.g., precipitation, atmospheric circulation intensity) that characterized it. While climate forcings such as solar variability and volcanism explain some degree of LIA climate, more complex multiple forcings and nonlinear responses to these forcings must be investigated. Therefore, while the LIA is the most recent example of a naturally forced cooler climate, our knowledge of this event is not sufficient to understand its significance or explain its causes. Less is known about the MWP. Understanding of modern climate is, therefore, hampered not only by questions concerning the influence of humanly induced forcing through emissions of radiatively important trace gases and aerosols but as fundamentally through a lack of understanding of the natural climate variability that underpins modern climate.

While significant progress has been made in the short-term prediction of important atmospheric phenomena such as ENSO, relatively little is understood about potential changes in the frequency and magnitude of this and other important climate systems (e.g., monsoons, North Atlantic hurricanes) on decadal and greater scales, despite evidence that such events did vary in frequency and magnitude over such periods as the LIA.

Holocene climate and environmental response have been sufficient to create significant stresses for emerging civilizations. Human impact on the chemistry of the atmosphere and on the land-ocean environment and climate has also been extremely significant. However, the complex interplay of human activity and environmental and climatic change still holds many unanswered questions (see Box 6.2).

Focus on the Past 250,000 Years

The interglacial climate we currently enjoy is known from paleoclimate records that cover the past 1 million years to be relatively rare. These records also demonstrate that interglacial climates appear coincident with the relatively rapid dissipation (several hundred to thousands of years) of glacial-age ice sheets and end more gradually as ice sheets re-encroach. Pioneering studies link the cadence of these glacial/interglacial cycles to insolation changes produced by changes in the Earth's orbit (Milankovitch cycles), yet not all details of event phasing or event frequency can be explained by these theoretically calculated insolation changes.

Ice core records from Antarctica have demonstrated the close linkage between temperature and the greenhouse gases CO_2 and CH_4. However, issues of phasing, particularly for CO_2, remain less well understood. Furthermore, despite their importance in climate forcing, changes in the concentration of greenhouse gases cannot fully explain documented changes in temperature.

Rapid climate change events recently developed from the central Greenland ice cores and since found in marine and terrestrial sediments punctuate the slower pattern of ice sheet growth and decay. From the highly resolved and well-dated Greenland ice cores comes evidence that many of these rapid climate change events occur in relatively predictable cycles of ~6,000 years (Heinrich events, first revealed from marine sediments as massive discharges of icebergs) or as massive atmosphere-ocean reorganizations that occur with ~1,500-year frequency (Dansgaard/Oeschger cycles).

Although globally distributed and dramatic in magnitude and timing, important characteristics of the rapid climate change events are still not clearly understood. These events were documented through the investigation of well-dated continuous records; to understand the phasing of these events from region to

**BOX 6.2 Key Scientific Questions: Stream One—
The Past 2,000 Years**

- Is the warming experienced during the twentieth century unusual?
- Are there major modes of subdecadal-, decadal-, and centennial-scale variability?
- Do certain regions of the Earth play leading roles in global climate change by either driving or responding to climate change (e.g., North Atlantic, Southern Ocean, tropics)?
- Are climate change events (e.g., LIA, MWP) synchronous in magnitude and timing in both hemispheres or do some display regional differences?
- Have major atmospheric circulation systems such as ENSO, Asian-Australian-African monsoon, and westerlies shifted over time? Is there a recognizable pattern to these changes? Why have these changes occurred? Are there regularities, synchronisms, or teleconnections that can be used for developing predictive model capability? Have these changes been in response to changes in other components of the climate system (e.g., sea surface temperature, snow cover, cloud cover)?
- How are atmospheric teleconnections manifested at regional to global scales and over decadal to century timescales?
- How has the hydrology of the planet changed over the past two millennia?
- How has the record of ENSO and its climate teleconnections changed over the past two millennia?
- How has the record of explosive volcanism changed over the past two millennia? How does this record relate to climate change?
- How do natural feedbacks (dusts, biogenic trace gases) operate and affect the climate system?
- How has solar irradiance varied over the past two millennia? What are the mechanisms by which changes in solar irradiance cause climate change? How has the environment responded to these variations?
- How has sea level changed over the past two millennia? How do ice sheets, mountain glaciers, and other changes in the hydrological cycle contribute to this change?
- How have ecosystems (e.g., equatorial rain forests, tundra, forest, steppe, glacial) responded to environmental change over the past two millennia?
- How has human activity impacted the environment?
- How have humans responded to environmental change?

region more such records will be required. Phasing information will be crucial in determining the cause of these events.

Changes in thermohaline circulation of the ocean are believed to play a major role in the production of rapid climate change events, but the causes of such changes are not well understood. Multiple nonlinear forcings that invoke internal ocean oscillations, changes in ocean-continent boundary conditions, solar variability, changes in the concentration of greenhouse gases and biogenic

BOX 6.3 Key Scientific Questions: Stream Two—The Past 250,000 Years

- Are there major modes of centennial- to millennial-scale variability?
- What is the phasing of climate evolution between the two hemispheres?
- How have changes in Milankovitch insolation cycles, thermohaline circulation, trace gases, aerosols, and solar variability affected climate evolution in the two hemispheres?
- Are the rapid climate change events recorded in the Greenland ice sheet found in the southern hemisphere? Are these events also found in marine and terrestrial records? Are these events synchronous in timing and magnitude?
- How have boundary conditions changed in specific regions (e.g., south Asian "warm pool," Tibetan Plateau) and have these changes caused responses in major atmospheric circulation systems such as ENSO, Asian-Australian monsoon, ITCZ, and jet streams?
- How are hydrological changes in the tropics related to climate change in extratropical regions? What causes these changes?
- How are changes in biomass productivity linked to changes in trace gases in the atmosphere?
- How has monsoonal circulation varied in the past and are these changes synchronous in different regions?

emissions, changes in the hydrological cycle, volcanism, and ice sheet dynamics superimposed on insolation cycles must be investigated through both more well-resolved and well-dated paleoclimate records and modeling efforts to understand rapid climate change events.

Glacial/interglacial cycles and rapid climate change events provide dramatic examples of the dynamic range of natural climate variability. As such these climate events offer excellent opportunities for examining global to regional-scale changes in atmospheric circulation patterns (e.g., ENSO, Asian-Australian monsoon, ITCZ, jet streams) (see Box 6.3).

LESSONS LEARNED

The task of understanding climate change and predicting future climate change is particularly complex. However, the paleoclimate record provides a series of lessons upon which our understanding can be constructed and tested. An understanding of climate change and an understanding of the consequences of this change are possible if the lessons learned from the paleoclimate record are considered.

The *first lesson* is that, while there are no true analogs for modern or future climate in the paleorecord, the modern instrumental record is too short and too undersampled to understand and predict the full range of climate change. There are, in fact, parts of the Earth (e.g., Antarctica, high-altitude sites) for which no multidecadal instrumental series are available. Yet these sites are often ideal for the recovery of paleodata (e.g., ice cores, lacustrine sediments, tree rings). The most robust paleodata are those that can be calibrated with instrumental records. A classic example is the perfect fit between modern atmospheric CO_2 and the CO_2 trapped in ice cores.[109] While paleodata may come from a variety of mediums and reveal a wide range of proxies to direct environmental indicators, such data are all we have short of a time machine. Unfortunately, the paleorecord is also severely undersampled in time and space.

The *second lesson* is that only from the perspective of paleoclimate records can patterns, trends, thresholds, and ranges of natural climate variability (both unforced and naturally forced) be assessed. Recognition of potential "surprises" in natural climate variability, such as rapid climate change events, ENSO, and drought recurrence, require long backward glances to assure proper perspective. As a corollary to this it is clear that the paleoclimate record is essential as a basis for quantifying signal to noise ratios in shorter observational records. It will not be possible to assess interannual- to decadal-scale signal to noise in expensive satellite-based measurements until well into the twenty-first century, at which time too much will have been invested to make a mistake. It will be impossible to assess decadal- to centennial-scale variability without data collections that extend well into the twenty-second century.

The *third lesson* is that regular patterns of climate variability can be identified on the decadal-to-millennial scales. This finding is particularly encouraging since one of the end goals of climate change research is predictability. It is also apparent that there are significant temporal and spatial differences in climate variability. Deconvolving predictable patterns at the regional scale and determining the temporal baseline from which predictably can be assessed will require a considerably more dense spacing of paleodata.

The *fourth lesson* is that it is not possible to utilize modern instrumental records, which characteristically cover a century or less, to understand natural climate variability because these data series are too short and record mixed responses to natural and anthropogenic forcing of climate. However, natural climate variability is a major component of modern and future climate. Only paleodata covering periods prior to the past century can be considered to reflect natural responses to natural forcing. The paleorecord provides a unique testbed for assessing relative differences in the significance of natural climate forcings (e.g., solar variability, greenhouse gases, sulfate aerosols) over time and space. Only the paleoview provides the recognition and understanding that climate change is the cumulative effect of causal mechanisms that operate over short to long timescales. Furthermore, it is not likely that absolutely unambiguous determinations of the natural background state for atmospheric chemistry can be determined without examining paleodata.

The *fifth lesson* is that the value of high-resolution (subannual to annual), annually resolved, continuous, and multivariate paleodata provide the best opportunity for step function advances. A new standard for this type of record has been set by the Greenland ice cores, but too few such datasets exist. These records provide a new framework for examining shorter, less well resolved, discontinuous paleodata. Not all paleorecords allow annually resolved dating. Some depend on other dating techniques that include, for example, modeling, ^{14}C dating, and stratigraphic markers. Extensive efforts will be required to remove limitations in these techniques. For example, ^{14}C reservoir effects in oceans and lakes are not well understood. The value of less well resolved, even discontinuous, records should not, however, be underestimated as a tool for exploration and as a stimulus for new ideas. A classic example comes from a 1987 examination of beetle remains in Britain, which demonstrated the potential for rapid onset and decay of the Younger Dryas event.[110]

The *sixth lesson* is that, while spatially dense networks of paleodata are preferable in some cases, single sites can provide significant results if the records are well dated, continuous, of high resolution, and multivariate. Such records may prove to be of immense value because they are close to major environmental transitions or because they allow measurement of variables that reflect local- to regional- to global-scale change depending on the measurements.

The *seventh lesson* is that paleodata provide a wide range of case studies for assessing human, animal, and plant responses to a variety of environmental changes, such as shifts in atmospheric circulation, temperature, and moisture availability.

RESEARCH IMPERATIVES

During the past decade paleoclimate research has made dramatic advances that built on a strong background of previous research. New records have emerged that reveal rapid changes in climate that operate on scales and at magnitudes that are of crucial relevance to human society. The paleoclimate record has revealed the complexity of both climate response and climate forcing and variations of both in time and space. While complex, the identification of recurring patterns in some climate records offers promise for future understanding and prediction. Furthermore, considerable advances have been made in our understanding of environmental response to climate. Paleoclimate studies literally stand on a threshold of understanding that will continue to expand if fueled by future research. The research imperatives are as follows:

- Document how the global climate and the Earth's environment have changed in the past and determine the factors that caused these changes. Explore how this knowledge can be applied to understand future climate and environmental change.

- Document how the activities of humans have affected the global environment and climate and determine how these effects can be differentiated from natural variability. Describe what constitutes the natural environment prior to human intervention.
- Explore the question of what the natural limits are of the global environment and determine how changes in the boundary conditions for this natural environment are manifested.
- Document the important forcing factors that are and will control climate change on societal timescales (season to century). Determine what the causes were of the rapid climate change events and rapid transitions in climate state.

Paleoclimate records come from a variety of archives (e.g., tree rings, ice cores, marine and lake sediments, corals, historical documents) and are available at a variety of resolutions and age ranges. Paleoclimate records also provide different types of information ranging from proxy to direct. Furthermore, they contain evidence of both environmental response to change and the potential causes of change. A broad range of types of records will be required to understand climate change. No one type of record will suffice, since no single record type can provide the temporal, spatial, proxy, and direct measurements required to develop the global array required to understand past changes in climate.

Our most detailed view of climate comes from the past few decades of instrumented observations. To take the fullest advantage of paleoclimate records, calibration between paleoclimate and instrumented records is essential. Landmark examples already exist, notably the calibration between CO_2 measurements in ice cores and CO_2 observations in the atmosphere. Preliminary comparisons between coral, tree ring, and ice core paleoclimate series and instrumental series of, for example, ENSO and the NAO are extremely encouraging.

Paleoclimate studies calibrated to instrumental series offer the "missing years" prior to the introduction of Earth-observing satellites and instrumented observations. These missing years cannot be produced by any other known methodology. Furthermore, through the hindsight offered by paleoclimate records, observing programs will be able to more accurately assess natural climate variability, patterns, trends, and signal to noise. Finally, paleoclimate records offer the climate modeling community a bold opportunity for testing climate response and forcing on a variety of timescales and resolutions heretofore untouched.

Nine guiding principles for future research are as follows:

1. Development of a global array of highly resolved, continuous, precisely dated, multivariate paleoclimate records that sample the atmosphere, ocean, cryosphere, and land. For the identification of environmental change over the past two millennia, annual to decadal resolution will be required, and for longer timescales decadal- to centennial-scale resolu-

tion will be needed. Continuously sampled and precisely dated records are essential. Tree ring and more recently ice core studies have set a standard of annually resolved dating that should be adhered to wherever possible. Multiproxy paleorecords should be developed wherever possible to maximize interpretations. The primary purpose of this global array should be to specify change over critical regions and during critical periods. For example, a major focus should include investigation of the frequency and extent of rapid climate change events (millennial to ENSO range) and identification of the controls on such events.

2. Long paleodata series (centennial- to millennial-scale) should be complemented by spatial arrays of shorter records (decades) to enhance record interpretations and allow differentiation of local versus regional and wider environmental signals.
3. Integration and detailed calibration of paleodata and observational series will be essential. This approach will allow hindcasting of the relatively short timescale observational series. With coupled instrumental/paleodata series, it will be possible to specify the frequency and magnitude of variability for major atmospheric circulation systems (e.g., ENSO, NAO, North Pacific Oscillation) and extreme events (e.g., droughts, floods).
4. Paleoclimate and observational series should be coupled with process studies to specify controls on climate behavior. Ground-based and remote observing systems afford a unique tool for studying processes. Such studies should be closely integrated with existing observational sites and regions from which valuable paleodata series may be collected. Future ground-based stations and satellite observations should be planned with paleodata in mind.
5. A clear demonstration of the "natural state of environmental variability" is needed as a baseline for assessing the influence of anthropogenic forcing on climate change. This will require the collection and interpretation of a broad array of paleodata series that capture variability in the physical, chemical, and biological boundary conditions down to regional and in some cases locally specific areas over several timescales.
6. Time-dependent modeling of climate behavior is required that is explicitly designed to test paleoclimate event histories, address boundary conditions present during periods of purely natural climate forcing and boundary conditions for the modern climate era where complex interactions of an anthropogenically forced climate are superimposed on a system of naturally varying climate.
7. Improved dating techniques are required for paleodata. While annually resolved records are available from tree rings and some ice cores, most paleoseries are dated by models, spot relative and absolute dating, and spot marker horizons. Great advances have been made in ^{14}C dating of small-volume materials and the identification of unique events such as globally distributed volcanic events, but more work is needed.

8. More unique tracers are needed to reconstruct ocean and air mass trajectories. Unique chemical signatures have proven to be valuable tracers for atmospheric circulation systems, but more work is needed.
9. Free and open exchange of paleodata and other data (e.g., instrumental, satellite, ground-based) is essential if continued progress is to be made in global environmental change.

Over the past few decades science has demonstrated the impact of human activity on the environment and has realized the importance of natural variability in climate. As a consequence of both natural forces and human activities, climate change and environmental change are now known to be inevitable. What is not known are the rates, frequency, and magnitude of these changes and the exact controls on them.

As inextricably as our understanding of the Earth is dependent on viewing it as a complex system from space, thus assuring a view of the whole system, so too is it inextricably true that this understanding must include the evolution over years to millennia of the Earth system as a major goal. Paleoclimate records offer the temporal perspective of years to millennia. Within the paleoclimate record are the answers to principal scientific questions. Does climate evolve or is it chaotic? Is climate predictable and at what resolutions?

Many major advances in our understanding of climate would not have come without paleoclimate research. Although paleoclimate reconstructions are not absolute truth, when based on high-quality records they are the best information available for understanding past climate changes. Paleoclimate reconstructions provide fertile ground for modeling, and those involving multiple records that have broad geographic coverage and multiple-proxy capability should be encouraged as input to models. The results of these model experiments undertaken in an iterative mode and incorporated into paleoclimate reconstructions hold great promise for increasing our understanding of climate change.

Based on paleoclimate research we now realize the following:

- The Earth's orbital cycles of insolation provide the cadence for glacial/interglacial cycles.
- Greenhouse gas concentrations and biogenic emissions are closely linked to temperature.
- Rapid climate change events that operate at magnitudes and rates significant to humans have operated throughout at least the past glacial/interglacial cycle.
- Human influences on the chemistry of the atmosphere (e.g., trace gases, aerosols, trace metals) exceed rates and magnitudes measured over the past few million years.
- Climate change is produced by single forcings (e.g., volcanism) and multiple forcings that can act nonlinearly to produce climate "surprises."

NOTES

1. CLIMAP Project Members (1976, 1981), COHMAP Members (1988), Hays et al. (1976), Imbrie et al. (1984, 1989).
2. E.g., Hays et al. (1969), Imbrie et al. (1973).
3. Jouzel et al. (1987), Barnola et al. (1987).
4. Taylor et al. (1993), Grootes et al. (1993).
5. Annual layer counting, Alley et al. (1993), Meese et al. (1994a); ice core, Bender et al. (1994).
6. Alley et al. (1993), Meese et al. (1994a, b), Sowers et al. (1993).
7. Cuffey et al. (1995).
8. E.g., Birchfield and Weertman (1983), LeTreut and Ghil (1983), Budd and Smith (1987).
9. Snow accumulation, Alley et al. (1993); magnitude changes, Mayewski et al. (1993); methane, Brook et al. (1996).
10. Alley et al. (1993), Mayewski et al. (1993), Taylor et al. (1993).
11. Chappellaz et al. (1993).
12. Bender et al. (1994).
13. E.g., Heinrich, (1988), Broecker et al. (1992), Bond et al. (1992), Andrews and Tedesco (1992), Lehman and Keigwin (1992).
14. E.g., Ruddiman and McIntyre (1981), Boyle and Keigwin (1987).
15. Oppo and Lehman (1995).
16. Discharge events, Heinrich (1988); ice sheet dynamics, MacAyeal (1993).
17. Bond et al. (1993), Mayewski et al. (1994), Cortijo et al. (1995), Bond and Lotti (1995).
18. Kennett and Ingram (1995), Behl and Kennett (1996), and Kotlainen and Shackleton (1995).
19. Porter and An (1995).
20. Lowell et al. (1995).
21. Sowers and Bender (1995).
22. Broecker and Denton (1989).
23. Stute et al. (1995).
24. Thompson et al. (1995).
25. CLIMAP Project Members (1981).
26. Broecker (1996).
27. Cortijo et al.(1995), Sirocko et al. (1996), Mayewski et al. (1997).
28. Mayewski et al. (1997).
29. E.g., Denton and Karlen (1973), Harvey (1980).
30. E.g., Overpeck et al. (1992).
31. Diaz et al. (1989).
32. Delcourt and Delcourt (1987), Huntley and Webb (1988), Davis (1990), Prentice et al. (1991), Overpeck (1993).
33. Overpeck et al. (1991).
34. E.g., Meese et al. (1994b), O'Brien et al. (1996).
35. Circulation systems, Mayewski et al. (1994, 1997); paleoclimate records, Denton and Karlen, (1973), Harvey (1980), Alley et al. (1997); coolings, O'Brien et al. (1996).
36. E.g., Denton and Karlen (1973), Stuiver and Braziunas (1989), O'Brien et al. (1995).
37. O'Brien et al. (1996).
38. Street-Perrott and Perrott (1990).
39. Stager and Mayewski (1997).
40. African lake levels, e.g., Gasse and Van Campo (1994), Stager et al. (1997), Lamb et al. (1995); Dead Sea levels, Klein (1986), Frumkin et al. (1991).
41. Sirocko et al. (1993).
42. Indian monsoon, Overpeck et al. (1996); earlier reports, Kutzbach (1987), Clemens et al. (1991).

43. COHMAP members (1988), Overpeck et al. (1996).
44. Houghton et al. (1992).
45. E.g., Street-Perrott and Perrott (1990), Hodell et al. (1991, 1995), Ely et al. (1993), Knox (1993).
46. (1) E.g., Broecker (1987), Broecker et al. (1992); (2) insolation, Thomson (1995); moisture and temperature, McIntyre and Molfino, (1996); (3) e.g., Denton and Karlen (1973), Damon et al. (1989), Damon and Jirikowic (1992), Stuiver and Braziunas (1993).
47. Solar variability, Stuiver and Braziunas (1993); ^{10}Be series from ice cores, Finkel and Nishiizumi (1997); CO_2 from ice cores, e.g., Barnola et al. (1987), Wahlen et al. (1991), Etheridge et al. (1996); CH_4 from ice cores, Chappellaz et al. (1993), Blunier et al. (1995), Brook et al. (1996); volcanic sulfate from ice cores, Zielinski et al. (1994, 1996).
48. Grove (1988).
49. Zhang and Crowley (1989).
50. O'Brien et al. (1996).
51. Thompson and Mosley-Thompson (1987).
52. Keigwin (1996).
53. Ibid.
54. Houghton et al. (1992).
55. Stine (1994).
56. Anderson (1992).
57. Enfield and Cid (1991).
58. Regions, Ebbesmeyer et al. (1991); ITCZ, e.g., Mann et al. (1995), Linsley et al. (1994), Cole et al. (1993), Dunbar et al. (1994); midlatitudes, e.g., Boninsegna (1992).
59. E.g., Bradley and Jones (1993), Mosley-Thompson et al. (1993), Hughes and Diaz (1994).
60. Solar output, e.g., Eddy (1976, 1977), Jirikowic and Damon (1994), Lean et al. (1995); aerosols, e.g., Stothers (1984), Bradley (1988), Scuderi (1990); aerosol loading, Porter (1981, 1986); thermohaline circulation, Weyl (1968), Watts (1985).
61. E.g., Dickinson and Henderson-Sellers (1988), Henderson-Sellers and Gornitz (1984).
62. Bonan et al. (1992).
63. E.g., Cook et al. (1996a).
64. Briffa et al. (1992).
65. Fritts (1991).
66. Meko et al. (1993), Cook et al. (1996b).
67. Historical records, Quinn et al. (1978, 1987), Quinn (1992); tropical corals, Cole et al. (1992); tropical ice cores, Thompson et al. (1992); polar ice cores, Legrand and Feniet-Saigne (1991).
68. Cole et al. (1992).
69. Barlow et al. (1993), White et al. (1997).
70. Antarctic, Welch et al. (1993); Arctic, Grumet et al. (1998).
71. Etheridge et al. (1996).
72. Mayewski et al. (1990).
73. Lyons et al. (1990).
74. Tree rings, Stuiver and Braziunas (1993); Greenland ice core, Beer et al. (1994).
75. Beer et al. (1994).
76. Henderson-Sellers et al. (1995a, 1995b).
77. Holdridge (1947), Prentice et al. (1992).
78. Bergengren (1994), Bergengren et al. (1997).
79. Prentice et al. (1993).
80. Henderson-Sellers and McGuffie (1995).
81. Huntley and Webb (1988).
82. Vegetation maps, Wolfe (1985); updates, Berhensmeyer and Potts (1992).

83. Wing and Greenwood (1993).
84. Spicer and Corfield (1992), Spicer et al. (1993).
85. Mangan (1996).
86. Pollard and Thompson (1995a, 1995b).
87. DeConto et al. (1997).
88. E.g., Woodward (1987), Kurschner (1996), Kurschner et al. (1996).
89. Cerling et al. (1993).
90. E.g., Berner et al. (1983), Berner (1991), Freeman and Hayes (1992), Cerling (1991).
91. Clark (1977).
92. Smiley (1967).
93. Spicer and Parrish (1990), Spicer and Corfield (1992).
94. Berner (1991), Freeman and Hayes (1992), Cerling (1991).
95. Shackleton and Boersma (1981), Keigwin and Corliss (1986), Zachos et al. (1994).
96. E.g., Estes and Hutchinson (1980), McKenna (1980), Wolfe (1980).
97. Wing and Greenwood (1993).
98. Berner (1991).
99. Barron et al. (1995).
100. Shackleton and Boersma (1981), Sloan and Barron (1990).
101. Spelman and Manabe (1984), Covey and Thompson (1989), Rind and Chandler (1991), Barron and Peterson (1990, 1991), Barron et al. (1995).
102. Rind and Chandler (1991), Barron et al. (1995).
103. E.g., Hansen and Lacis (1990), Lorius et al. (1990), Hoffert and Covey (1992), Crowley (1993).
104. Hoffert and Covey (1992).
105. Crowley (1993).
106. Barron et al. (1995).
107. Berner (1991), Freeman and Hayes (1992), Cerling (1991).
108. PANASH (1995), CLIVAR (1994).
109. Etheridge et al. (1996).
110. Atkinson et al. (1987).

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7

Human Dimensions of Global Environmental Change*

SUMMARY

Research on the human dimensions of global change concerns human activities that alter the Earth's environment, the driving forces of those activities, the consequences of environmental change for societies and economies, and human responses to the experience or expectation of global change. Such research is essential both to understand global change and to inform public policy.

Research on the human causes of global change has shown that socioeconomic uncertainties dominate biophysical uncertainties in climate impacts and possibly also in other impacts of global change. It has shown that human activities, such as deforestation and energy consumption, are determined by population growth, economic and technological development, cultural forces, values and beliefs, institutions and policies, and the interactions among all these things. Ongoing research is improving our understanding of the dynamics of several of these driving forces. It has shown, for example, that human interactions with the environment do not necessarily lead to a "tragedy of the commons" and has begun to enumerate the necessary conditions for successful long-term environmental resource management. Research on the human consequences of global change shows that they are due at least as much to the social systems that produce vulnerability as to environmental changes themselves. This work is refining estimates of impacts and identifying major sources of vulnerability. Research on

* This chapter was written by the National Research Council Committee on the Human Dimensions of Global Change, with contributions and editing by the Committee on Global Change Research.

human responses is continually developing and applying better analytical procedures to estimate the costs of global change and policy response options, considering their dependence on highly contestable judgments about nonmarket values and intergenerational equity. Much human response research is focused on the design of human institutions to reduce vulnerability and manage global resources more effectively.

Research over the past decade has made considerable progress, but there are still many unresolved questions. Key research imperatives for the next decade are the following:

- *Understanding the social determinants of environmentally significant consumption*. Research should focus on the most environmentally significant consumption types, changes in consumption patterns as a function of economic growth and development, materials transformations, and the potential for related policy changes. Consumption is a key variable driving trends and patterns in the human impact on atmospheric composition, land use, and biogeochemical cycles.
- *Understanding the sources and processes of technological change.* Research must address the causes of "autonomous" decreases in energy intensity, determinants of the adoption of environmental technologies, and effects of alternative policies on rates of innovation and the role of technology in causing or mitigating global changes.
- *Making climate change assessments and predictions regionally relevant.* Research must develop indicators for vulnerability, project future vulnerability to climatic events, link climate change with social and economic changes in projections of overall regional impacts and their distribution, and improve communication and warning systems, especially in view of recent developments in forecasting.
- *Assessing social and environmental surprises.* The historical record of social and environmental surprises must be explored to clarify the consequences of major surprises, identify human activities that alter their likelihood, and better understand how communication and hazard management systems can help in responding to surprises.
- *Understanding institutions for managing global change.* Research should clarify the conditions favoring institutional success or failure in resource management; the links among international, national, and local institutions; and the potential of various policy instruments, including market-based instruments and property rights institutions, for altering the trajectories of anthropogenic global changes.
- *Understanding land use/land cover dynamics and human migration.* This research should examine and compare case studies of land use and land cover change; develop a typology that links social and economic driving forces to land cover dynamics; and model land use changes at regional

and global scales, particularly as they affect ecosystems and biogeochemical cycles and the human consequences of environmental change.

- *Improving methods for decision making about global change.* Research should improve ways of estimating nonmarket values of environmental resources, incorporating these values into national accounts, representing uncertainty to decision makers, and structuring decision-making procedures and techniques of scientific analysis so as to bring formal analyses together with judgments and thus better meet the needs of decision-making participants.
- *Improving the integration of human dimensions research with other global change research.* Human dimensions research supports each of the other fields of scientific research on global change and also addresses key cross-cutting issues. It requires focused and coordinated support that draws on the strengths of both disciplinary and interdisciplinary approaches and that takes advantage of value added by international collaborations.
- *Improving geographic links to existing social, economic, and health data.* Human dimensions data systems benefit from adding geographic information to ongoing social data collection efforts, with appropriate safeguards for confidentiality. The effectiveness of these data systems depends on adequate and stable support. The time is ripe for a careful review of the observational needs for human dimensions research, with careful attention to the ability to link to other observational systems.

INTRODUCTION

Study of the human dimensions of global environmental change encompasses analysis of the human causes of global environmental transformations, the consequences of such changes for societies and economies, and the ways in which people and institutions respond to the changes. It also involves the broader social, political, and economic processes and institutions that frame human interactions with the environment and influence human behavior and decisions. Significant among these are the processes and institutions that use scientific information about environmental processes and human-environment interactions as inputs to human choices that alter the course of those processes and interactions. Thus, one of the human dimensions of global change involves the practical use of scientific information and the issue of how to make such information more useful for decision making. Beginning with a focus on climate change, human dimensions research is expanding to address changes in biodiversity, land and water, pollution, and other globally significant resources and to draw on the extensive literature that addresses human-environment interactions.

Human transformations of the global environment have a long history. Table 7.1 shows that, since 1700, human activity has converted 19 percent of the world's forests and woodlands to cropland and pasture. This shift has altered bio-

TABLE 7.1 Changes in Land Cover, 1700 to 1980

Land Cover Type	Area in 1700 (millions of hectares)	Area in 1980 (millions of hectares)
Forest and woodlands	6,215	5,053
Grassland and pasture	6,860	6,788
Croplands	265	1,501

SOURCE: Adapted from Richards (1990). Courtesy of Cambridge University Press.

geochemical cycles, land surface characteristics, and ecosystems so much that the Earth system itself has changed significantly.

Human activity, especially fossil fuel consumption since the Industrial Revolution, is also responsible for substantial increases in atmospheric concentrations of such gases as carbon dioxide and methane. These increases (see Table 7.2) are mostly associated with the per capita consumption of fossil fuels and growth of the human population; deforestation and the production of cement, livestock, and rice for human consumption; the disposal of wastes from human settlement in landfills; and increased use of fertilizers and industrial and agricultural chemicals. The likely consequences of these gas emissions include a warming of the global climate and a reduction in stratospheric ozone.

Such human activities have accelerated rapidly in recent decades. Between 1950 and 2000 the world's population will have increased from 2.5 billion to more than 6 billion people. Total energy consumption increased from 188,000 petajoules annually in 1970 to almost 300,000 petajoules in 1990, and per capita energy consumption increased from about 50 to 57 gigajoules.[1] Between 1970 and 1990, global forest area decreased by 6 percent, irrigated area increased by almost 40 percent, number of cattle increased by 25 percent, and use of chemical fertilizers doubled.[2]

TABLE 7.2 Greenhouse Gas Concentrations, Preindustrial Age to 1984

Greenhouse Gas	Preindustrial Age	1994	1990s Rate of Change per Year (%)
CO_2	280 ppmv	358 ppm	0.4
CH_4	700 ppbv	1,720 ppb	0.6
N_2O	275 ppbv	312 ppb	0.25
CFC_{11}	0 ppt	268 ppt	0 (HCFC 5%)

NOTES: ppmv, parts per million (volume); ppbv, parts per billion (volume); pptv, parts per trillion (volume).

SOURCE: Intergovernmental Panel on Climate Change (IPCC) (1996b). Courtesy of the IPCC.

These changes, which have altered global environmental parameters, are also associated with improved quality of life for many people: average life expectancy has increased 40 percent since 1955—from 47.5 years then to 65 years in 1995—and infant mortality decreased 60 percent—from 155 deaths per 1,000 in 1955 to 60 in 1990.[3] The rising global averages of per capita energy use, life expectancy, and infant mortality subsume vast disparities. People do not all contribute equally to global change nor benefit equally from progress. The processes determining these changes, sometimes called driving forces, also differ substantially across regions and populations, affecting future trends in both environmental quality and human well-being.

Regional differences in rates of environmental transformation reflect variations in the human driving forces of global change. In the case of greenhouse gas emissions the increase in coal production in China from 7,400 to 21,700 petajoules from 1970 to 1990 represents a doubling of per capita energy consumption due to economic development and national policies. In Mexico oil production grew from 980 to 6,046 petajoules over the same period, reflecting a doubling in per capita energy consumption, significant population growth, and national development policy choices to increase the export of oil. A loss of 40 million hectares of forest in Brazil since 1970 has significant implications for tropical biodiversity, as do losses of almost 10 million hectares each in Indonesia, Thailand, and Mexico. These trends in deforestation result from different combinations of population growth, migration, and economic and policy forces.[4] A major focus of human dimensions research is explaining patterns and changes in the rates of environmental transformation in terms of driving forces that act globally, regionally, and at the level of responsible decision makers.

The impacts of global change on societies and economies are expected to increase greatly in the next century. For example, much of the global change that will eventually result from past human activities has yet to occur, and current trends in these activities portend potential large increases in global change. As the major climatic changes lie in the future, so do their implications for humanity. This may also be true for the human consequences of ecological transformations now occurring through deforestation and other anthropogenic land cover changes. Thus, another major focus of human dimensions research is estimating the social and economic consequences of anticipated global environmental changes. This research integrates information about anticipated environmental changes with information on the social parameters that determine the impact of those changes: demand for affected natural resources, vulnerability of geographical regions and social groups to particular environmental changes, and the potential for adaptive response. In addition, human dimensions research addresses the workings of social systems that manage environmental resources—markets, property rights regimes, treaties, legal and informal norms, and so forth—and the potential to modify those institutions through policy and thus to mitigate global change or increase adaptive capability.

In sum, human dimensions research aims at understanding how human activity drives greenhouse gas emissions, regional air quality, land cover change, and alterations in terrestrial and marine ecosystems; predicting the course of the activities that drive those transformations; estimating how changes in climate, land cover, ecosystems, and atmospheric chemistry affect food, water, natural resources, human health, and the economy; analyzing the ways that societies manage environmental resources; and analyzing the feasibility and possible costs and implications of technical, economic, behavioral, and policy responses to those environmental changes. This research builds basic understanding of human-environment interactions and provides information and responsive tools to decision makers.

Although research on the social and policy aspects of environmental change has a long history, human dimensions research only became formally linked to global change research in the late 1980s. The potential for making this link was set forth in seminal writings addressed to national and international research policy makers.[5] Human dimensions research became part of the U.S. Global Change Research Program (USGCRP) in 1989 with a small National Science Foundation (NSF) program and has since become a significant component of the USGCRP. This activity, together with more general support from government, foundations, and universities for social science research on global change, has resulted in some significant accomplishments and insights in understanding the human dimensions of global climate change.

CASE STUDIES: CONTRIBUTIONS OF HUMAN DIMENSIONS RESEARCH IN ADDRESSING GLOBAL CHANGE

Human Dimensions Research and the IPCC

Contributions to the recent Intergovernmental Panel on Climate Change (IPCC) reports are a good illustration of the significance and policy relevance of human dimensions research. The year 1988 is often identified as a turning point in public and political perceptions of climate change in the United States. While the news media linked drought to global warming, scientists, environmental groups, and decision makers gathered in Toronto to declare the need for a 20 percent cut in greenhouse gas emissions.[6] Meanwhile, social and applied scientists were working to develop methods for assessing the economic and social consequences of climate change and examining the implications of the policies that might be used to mitigate it. The results of this research were reported to the IPCC and became an important part of international debate and decision making in response to the threat of climate change.

For example, demographers, geographers, and others have estimated populations at risk from sea level rise and demonstrated the tremendous vulnerability of many large cities to climatic variations.[7] The synthesized results of many country case studies indicated many billions of U.S. dollars in potential losses and protection costs associated with a 1-meter rise in sea level (see Table 7.3).

TABLE 7.3 Impacts of a 1-Meter Sea Level Rise in Selected Countries

Country	People Affected (millions)	Economic Loss (billions of U.S. dollars)	Land Area Lost (km^2)	Protection Cost (billions of U.S. dollars)
Bangladesh	71	NA	25,000	1+
China	72	NA	35,000	NA
Egypt	4.7	59	5,800	13.1
Japan	15.4	849	2,300	156
Netherlands	10	186	2,165	12.3
United States	NA	NA	31,600	156

NOTE: NA, not available.

SOURCE: Bijlsma (1996). Courtesy of Intergovernmental Panel on Climate Change (IPCC).

To estimate the potential effects of global warming on the world's food system, agronomists and economists linked the output of climate models to crop yield and economic models.[8] Figure 7.1 shows several important results of these studies, including the sensitivity of impact assessments to the results of different climate models, the considerable potential for adaptation to alter the impact of climate change, and the relative vulnerability of developing countries.

Also important to the IPCC and other assessments are efforts to calculate the costs and benefits of various mitigation strategies, such as carbon taxes and carbon sequestration through reforestation, including estimates of nonmarket values. For example, the estimated costs of a carbon tax to achieve a 20 percent reduction in CO_2 emissions ranged from $50 to $330 per ton of carbon in the IPCC study,[9] depending on the economic assumptions and model used. Forest plantations and forest management have the potential to sequester up to 75 billion tons of carbon a year.[10] Studies of the economic feasibility of this strategy have been used as a basis for discussions in the negotiations for the Framework Convention on Climate Change and have informed debate on strategies such as joint implementation of carbon reductions through aid for forest and energy efficiency projects.

Also considered by the IPCC was the issue of deforestation in Amazonia, where human dimensions research has informed policy decisions in Amazonian nations, especially Brazil, and in international organizations such as the World Bank. In the late 1980s international attention focused on Amazonia, where rapid deforestation was linked to climate change, loss of biodiversity, and threats to indigenous peoples.[11] Human dimensions research revealed the causes of forest destruction; for example, the building of highways opened the forest to migrants, many of whom did not know how to farm cleared land or manage forests sustainably.[12] Biases in agricultural subsidies, tax incentives, and high inflation promoted extensive land clearing for ranching.[13] Detailed social and spatial analyses of relationships among deforestation, secondary growth, and demo-

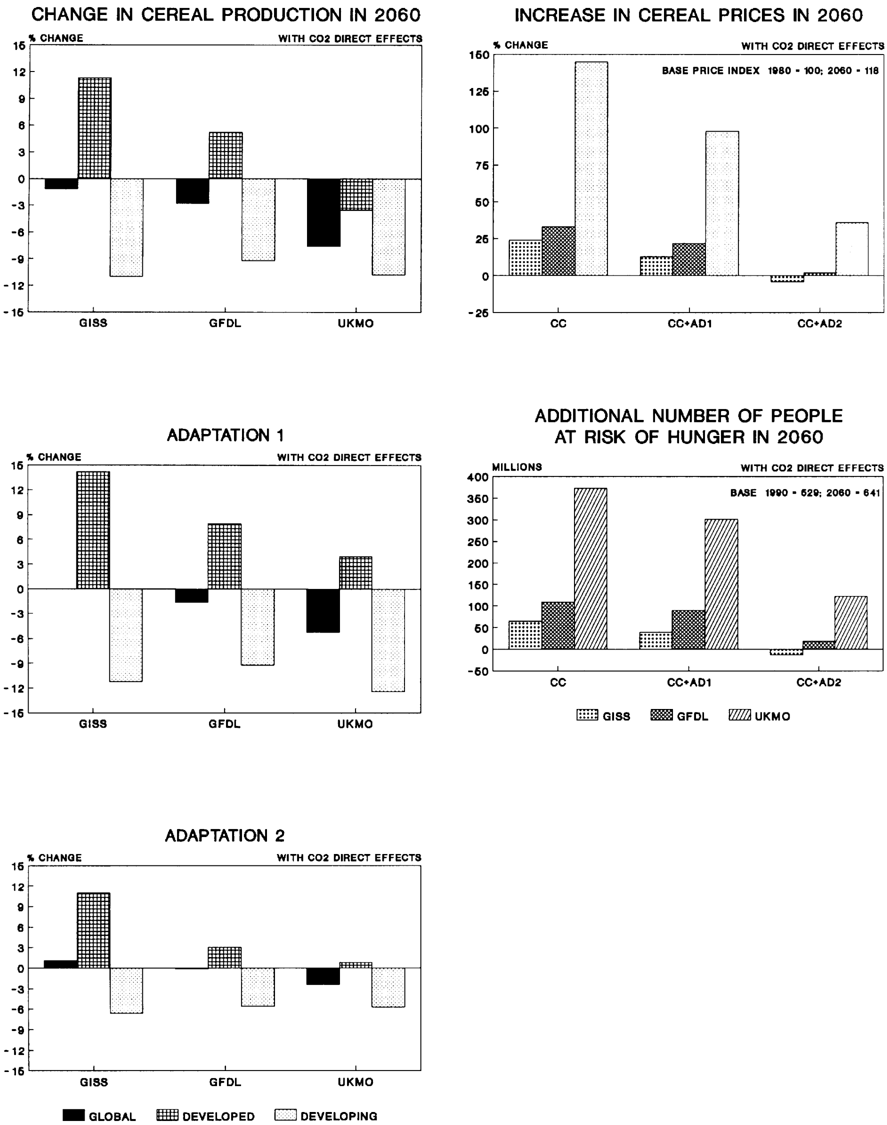

FIGURE 7.1 Change in global, developed country, and developing country cereal production, cereal prices, and people at risk of hunger in 2060 under different climate change scenarios (% change from a base estimate for 2060). NOTES: GISS, Goddard Institute of Space Science; GFDL, Geophysical Fluid Dynamics Laboratory; UKMO, U.K. Meteorological Office; CC, climate change scenario including direct CO_2 effects; Adaptation 1 (AD1), adaptation level involving minor changes to existing agricultural systems; Adaptation 2 (AD2), adaptation level involving major changes. Reference scenario assumes no climate change. SOURCE: Rosenzweig and Parry (1994). Courtesy of Macmillan Magazines Ltd.

graphic characteristics showed heterogeneous patterns that challenged simple explanations of land use change and showed the need for local strategies for ecosystem protection.[14]

Partly as a result of these research insights, countries such as Brazil have altered taxation and subsidy structures that favored ranching and have adopted policies for more sustainable development of forest lands. Multilateral development agencies now undertake environmental assessments for transportation and other development projects. Popular accounts are now more sensitive to the varied causes and responses to Amazonian deforestation.

Consequences of Climate Change and Variability at the Regional Level

Researchers have compiled data on overall losses from climatic disasters and have shown that economic damages are increasing dramatically, especially in the United States. For example, hurricane and flood losses have reached more than $1 billion annually in recent years and have stressed both federal disaster relief and private insurance systems.[15] Although these increased disaster losses may be due to climate change, much of the increase is a result of increasing vulnerability resulting from more people living in hazard-prone locations, increasing property prices, and inadequate land use and building regulations. In the developing world, millions of people have been displaced by cyclones, flooding, and droughts, as population growth, migration, and poverty expose more people to climatic extremes.[16] The human consequences of climate change and variability depend critically on the vulnerability of human populations and on their ability to adapt, as well as on climatic events.

Studies have also identified a serious threat of changes in the patterns of diseases and pests associated with climate change and variability.[17] The 1993 Midwest floods were associated with multiple epidemics in the United States. Heavy rains in Milwaukee overwhelmed the sanitation system, creating a plume of farm waste and contaminated runoff in Lake Michigan that later entered the water supply, resulting in a large outbreak of *Cryptosporidium* (400,000 cases, with more than 100 deaths). In Queens, New York, an exceptionally hot, humid summer boosted local mosquito populations, leading to local transmission of malaria. In the southwestern United States, intense rains provided a sudden burst of food supplies for rodents, following a six-year drought that significantly reduced rodent predators (owls, coyotes, and snakes). The 10-fold rise in rodents led to transmission of a "new" disease—hantavirus pulmonary syndrome—with a case fatality rate of 50 percent.

In Southern Africa, prolonged drought, punctuated by heavy rains in 1994, precipitated an upsurge of rodents, crippling agricultural yields in Zimbabwe and leading to plague in Mozambique and Malawi. In India in 1994 flooding following a summer of 51°C temperatures across the plains led to an outbreak of rodent-borne plague, as houses with stored grains heated up, generating clouds of fleas. In addition to severe human losses in the affected regions, measured economic losses included $2 billion to $5 billion by international airline and hotel chains from lost tourism.

Extreme weather events compounding local vulnerabilities (multiple stresses) can disrupt predator/prey relationships (functional biological diversity) and can generate biological surprises, such as population explosions of pests and pathogens that can affect human, plant, and animal health. The impacts of extreme events and epidemics can ripple through economies, affecting agriculture, productivity, trade, and tourism, in addition to their direct effects on regional human health and well-being.

There is, of course, much uncertainty about the role of climatic change in causing ecological changes that have costly effects on humans. A major recent example that highlights the difficulty in assigning causation is the collapse of the commercially important northern cod populations off the coast of eastern Newfoundland and Labrador, Canada, in the late 1980s and early 1990s. This collapse led to a costly program to compensate the over 30,000 people who could no longer work as fishers or fish processors. Debates continue about the roles of the North Atlantic Oscillation and other, more specific, climatic and oceanographic changes relative to the role of overfishing.[18] There is also uncertainty about the links from ecological consequences to human consequences because of gaps in knowledge about the ability of human communities to respond effectively to anticipated ecological changes.

In those regions where climatic variability is associated with El Niño-Southern Oscillation (ENSO) events, there is hope that improved understanding of sea surface temperatures and associated changes in atmospheric circulation will result in advance warnings of droughts, floods, and epidemics and reduced losses.[19] This type of human dimensions research highlights the importance of improved understanding of climate change and variability, the need to consider social vulnerability and adaptive capacity when forecasting the consequences of global change, the potential benefits of predicting climatic extremes, and the need to evaluate carefully options for reducing greenhouse gas emissions.

KEY SCIENTIFIC QUESTIONS

Key scientific questions for research on the human dimensions of global change can be grouped into four broad interrelated interdisciplinary categories:

- What are the major human causes of changes in the global environment and how do they vary over time, across space, and between economic sectors and social groups?
- What are the human consequences of global environmental change for key life support systems, such as water, health, and agriculture, and for economies and political systems?
- What are the potential human responses to global change? How effective

are they and at what cost? How do we value and decide among the range of options?

- What are the underlying social processes or driving forces behind the human relationship to the global environment, such as human attitudes and behavior, population dynamics, and economic transformation? How do they function to alter the global environment?

Research on the human dimensions of global change has value both as basic science and for informing environmental decisions. It increases basic understanding of how past human activities have created present environmental conditions, how past environmental changes and variations have affected human well-being, and how people have responded to these variations and changes. By developing understanding of human-environment dynamics, human dimensions research improves the knowledge base for anticipating future environmental changes and for informing policies aimed at reshaping the environmental future. Studies of the human consequences of and responses to global change help inform judgments about what kinds of responses would be most desirable (e.g., mitigation, adaptation options) and about how to organize those responses to achieve the desired effects. Below we describe the major science issues, review progress that has been made in understanding them, and identify some lessons that have been learned from previous research.

What Are the Major Human Causes of Changes in the Global Environment?

What has been learned in recent years about human causes of global environmental change? One major focus of research has been the explanation of changes in the composition of the Earth's atmosphere. Looking at the atmosphere through human history, one finds that the concentrations of several gases (carbon dioxide, methane, nitrous oxide) changed only a little for more than a thousand years and then started to increase rapidly around 1800. The obvious hypothesis to explain these data is that prior to industrialization in the nineteenth century the related basic cycles of the Earth's environment were in approximate equilibrium and aggregate human activity was too small to be detectable in globally averaged data; then, increasingly since the Industrial Revolution, aggregate human activity has changed the composition of the atmosphere, in particular adding measurably to the concentrations of certain gases. Similarly, looking at the history of land use and land cover, one finds significant changes occurring, although over longer time periods. The obvious hypothesis to explain these observations again is that human beings altered the land and used resources to meet the needs of a rapidly growing population and an expanding industrial economy. Research into the direct human causes of global change has thus focused on changes in land and energy use. But there is also a growing body of work on the fundamental social processes that drive human use of the environment.

Human Activity and Land Use Change

Interest in the causes of local and regional land use changes is long standing in the social sciences.[20] Significant steps have been made in documenting the long history of human transformation of land cover and in explaining the major forces that drive land use. These studies are of interest to a wide range of social and environmental scientists because land is a key factor in social relationships and resource use. But these studies also provide specific contributions to scientific understanding of biogeochemical cycles (especially the carbon cycle), regional climate modification, and alterations in natural ecosystems and are a critical basis for policies to mitigate and adapt to climate change, conserve biodiversity, and reduce land degradation.[21] Land use studies provide a powerful rationale for maintaining land and marine remote sensing satellite systems and suggest ways in which these technologies can be made more germane to decision making.

The global change research community has made considerable progress in recent years on several important questions, such as the social causes of deforestation in regions like the Amazon River basin and Southeast Asia; the role of social, political, and economic institutions in land use decisions; and the relationships between population and land use (and land cover) change.[22] There have also been tremendous improvements in the ability to combine social, physical, and remote sensing data within geographic information systems, often with the explicit purpose of understanding how processes at local scales are nested in regional, national, and global scales.[23]

Additionally, human dimensions research has highlighted the important distinction between land use and land cover. Whereas *land cover* refers to the land's physical attributes (e.g., forest, grassland), *land use* expresses the way such attributes have been transformed by human action (e.g., ranching, crop production, logging); that is, land use measures provide a socioeconomic portrait of a landscape.[24] Land cover is directly represented in global climate models. Land use links land cover to the human activities that transform the land.

The emerging field of environmental history has provided important data on the trajectories and causes of land use changes in the past. For example, historical studies of the U.S. Great Plains have shown how changes in the use and management of grazing and croplands relate to government policy and economics and in turn influence the cycling of carbon and nutrients.[25] Historians and geographers have also reconstructed the history of human use of such regions as the Mediterranean, Caribbean, and Latin America.[26]

Historical studies of land use have altered scientific thinking on the past and the present in a variety of ways. For instance, many observers have presumed that much of the humid tropical forests is pristine or that human impacts on the global environment mainly occurred in recent decades. However, research has shown that many forests were cleared in the distant past or have been managed for centuries and that their current rich biodiversity may be a product of past human manipulation, resulting in higher frequencies of species with economic, medicinal, and other human uses than might be expected to result from natural processes of secondary succession.[27]

Although human population growth is commonly seen as the major cause of land cover change and destruction of habitats for biota, particularly because of land clearing to grow food, the role of population is in fact far more complex. Numerous cases do suggest that population growth and/or migration are correlated with increasing rates of tropical deforestation, but just as many suggest that population growth need not lead to increasing deforestation—when alternative employment, settlement concentration, and other processes are available as alternatives to land clearing, to provide a population with an acceptable standard of living.[28] In fact, there is considerable evidence that only at higher population densities does one find more intensive and efficient use of land.[29]

Research on land management practices has demonstrated that overexploitation of common-pool natural resources—the so-called tragedy of the commons[30]—is not an inevitable consequence of human nature and the spatial distribution of resources but is contingent on the structure of human communities and the condition of social institutions that effectively govern access to a resource, monitor its condition, and establish sanctions for overexploitation.[31] Both cultural traditions and contemporary legal rules, such as land tenure rules, are critical in influencing how land can be used and by whom.

The emergence of integrated and interdisciplinary approaches to understanding land use and environmental issues has resulted in a series of studies that show how political and economic structures constrain individual choices about management of land and resources.[32] For example, colonial legacies of unequal land tenure and export-oriented production, combined with current unfavorable terms of trade and debt, have driven many peasants to overuse their land, adopt polluting technologies, or cut their forests.[33]

Social scientists have begun to make greater use of orbital Earth-observing satellites in recent years. The interest in understanding the social dimensions of land use change has challenged some of the inferences about land use drawn by natural scientists by showing, for example, the importance of secondary growth and the likely miscalculations of biomass and carbon pools resulting from overly aggregated analyses that fail to quantify the differences between mature and 10-year-old regrowth vegetation.[34] Social scientists have explained the processes underlying various patterns of forest change seen on satellite images in terms of the development of transportation networks, land tenure, and export agriculture. Social scientists have also made important contributions to explaining satellite observations of vegetation dynamics in Africa and to understanding land use change in areas undergoing urbanization.[35]

Field studies of land use have provided information of great relevance to global and regional atmosphere-biosphere modeling. For example, coarse-resolution satellite data tend to represent the predominant soil type or vegetation in each grid cell, even if a minor soil or vegetation type is of major economic or ecological significance. Such a representation of the data can seriously misrepresent land use and productivity potential as well as biogeochemical cycles. Another important development is the focus on explaining trends and patterns in land use intensification, in which crop yields are increased through the use of agricultural chemicals and irrigation, resulting in alterations in regional and global biogeochemical cycles and ecosystems.

Progress in the past decade is evident in the rise of an International Human Dimensions Programme/International Geosphere-Biosphere Programme (IHDP/IGBP) core project on land use/land cover change, with a coordinated, comparative, multilevel strategy for understanding, monitoring, and modeling land use.[36] In developing frameworks, case studies, and models of how social forces drive changes in land use and land cover, this type of comparative research program has the potential to explain and predict land use change but also to assist in identifying strategies for managing land use and protecting ecosystems.

Recent important U.S. initiatives include the expansion of the population program at the National Institute of Child Health and Human Development (NICHD) into population and environmental research in 1995, the creation in 1996 of an NSF-funded research center that works on land use—the Center for the Study of Institutions, Population and Environmental Change at Indiana University—and the National Aeronautics and Space Administration's (NASA) Land Use Cover Change request for proposals. In summary, there has been considerable progress in understanding the human causes of land use change, including the following insights:

- Humans have been altering land cover and use for centuries.
- Some regions that now appear pristine have been subject to human management since prehistoric times.
- There is no simple relationship between population and deforestation or between common property rights and resource degradation.
- The analysis of institutions—in their broadest sense, including political, legal, economic, and traditional institutions—and their interactions with individual decision making is critical in explaining land use.
- Satellite images can provide important insights for social science, and social science can help guide satellite programs to useful applications.
- The age and gender structure of landholding households affects how much forest is cut for farming.
- Tax incentives affect Amazonian deforestation.[37]
- Secure land tenure is important to long-term resource conservation.[38]

- Road construction in forests leads to increased deforestation not only by farmers claiming land but also by logging companies.

However, there is still inadequate knowledge on such key issues as these:

- How to develop land management institutions that both respond to local needs and mitigate global environmental change.
- How to aggregate in-depth studies of land cover and land use to provide global projections of use in large-scale modeling and international management of global change.
- The role of population mobility in land use change.
- How to best use the expanding range of satellite data in land use/land cover change research.

Human Impacts on Coastal and Marine Ecosystems

Global change research encompasses the study of changes in coastal and marine ecosystems insofar as they are affected by physical and socioeconomic processes that are global in scale and effect. Social and applied scientists have investigated the importance of coastal and marine ecosystems for many communities, regions, and nations. They have also addressed the ways in which resource use and pollution have altered the condition and biodiversity of coastal ecosystems in many regions of the world, including the destruction of protective and productive mangrove ecosystems, the degradation of coastal lagoons and estuaries and species that live or reproduce in them, and the minor contamination of even the deep and remote oceans.

Steady increases in demand, technological capacity, and effort have led to a long-term trend of increasing fish catches, which is believed to have leveled off during the 1990s, indicating limits to sustainable harvests.[39] Heavy fish mortality means that environmental fluctuations as well as other human impacts, such as pollution and degradation of habitat, make fisheries even more vulnerable.[40] Social scientists and others have documented the roles of technological change, population growth, institutional structures, and social attitudes in driving demand for fish and other marine resources, as well as in shaping the nature and effectiveness of fisheries management, and they have sought ways to use these resources more sustainably.[41] They have also contributed to understanding the ecological and social concerns associated with mariculture, which is increasing throughout the world as a way to compensate for declining natural resources.[42] This research also contributes to several related themes identified in this chapter, including the links between economic globalization (e.g., of industrial shrimp farming), conflicts over common property resources and loss of forest lands (mangroves); the emergence of new social institutions (social movements in resistance to industrial aquaculture); and the use of new information technologies (communications and spatial) in resource management.[43] Research on common property management, discussed in a later section of this chapter, has drawn many important examples from marine ecosystem use.[44]

Some important insights of this research include the following:

- People have responded to problems in coastal marine systems primarily by intensifying, diversifying, and expanding the areal extent of their uses of those systems, tending to extend such problems to the global level.
- Globalized systems of production and marketing, combined with increases in population and consumer demand and patterns of subsidization, increase competition between countries and communities for scarce marine resources.
- Rules of free and open access, combined with the weaknesses of international management regimes, make it difficult to control harvesting in deep ocean and other multinational fisheries.
- Restricting access is a necessary but not sufficient approach to reducing incentives to overharvest and pollute marine ecosystems.
- The technical and institutional tools of marine resource management have not adequately incorporated the effects of coastal development, wetlands drainage, dams, and pollution of rivers and oceans in diminishing breeding habitat and degrading marine resources.
- The success of fisheries and coastal management depends on functional interdependence between local institutions and regional, national, and international institutions.

Current knowledge is not adequate to achieve several essential goals:

- Provide complete geographic coverage of the status of human use of marine and coastal resources.
- Analyze and model changes in the abundance of fish and marine mammal populations as a function of multiple social and environmental stresses, including interannual, decadal, and longer-term climatic change.
- Evaluate the full range of institutions, including traditional systems, to understand how they increase or reduce human impacts on coasts and oceans.

Changes in Energy and Materials Use

Fossil fuel use is the most prominent human activity that alters the composition of the global atmosphere. Since the 1970s, a burst of human dimensions research seeking to understand the consumption of fossil fuels has been proceeding simultaneously at several levels. The methods developed for studying energy use have more recently been applied to human transformations of the global nitrogen cycle and to human consumption of other environmentally significant materials. The results are useful as inputs to climate models, for anticipating future rates of environmental change, and for identifying effective ways to mobilize social and economic forces to alter trajectories of environmental change.

First, fossil fuel use has been disaggregated by fuel type, geographic region, mediating technology, and social purpose (lighting, water heating, transportation, steel making, etc.). It has been shown that patterns and environmental impacts vary greatly by country and that national-level consumption varies with technology, population, and other factors, such as industrialization and degree of central planning of economies.[45]

Second, progress has been made in understanding patterns and changes in energy and materials use across countries and over time.[46] Energy use and its environmental impacts, for example, generally increase as a function of economic prosperity, but there are exceptions. Countries beyond a certain level of affluence experience declines in per capita environmental impact, although considerable dispute remains about where the turning point lies.[47] Also, the energy-affluence link breaks down in certain periods, including those characterized by rapidly increasing relative energy prices and significant policy interventions.[48] Thus, changes in prices and policies allowed economic growth to continue in the United States without increases in energy use or carbon emissions between the mid-1970s and the mid-1980s, but energy use has been increasing since then, driven by increasing travel demand, shifts in the vehicle fleet, and other factors, and similar trends have been occurring in other developed countries.[49] Long-term trends show decreasing carbon emissions per unit of energy use due to fuel switching and electrification, decreasing materials use per unit of economic output, and replacement of dense materials such as steel with lighter-weight materials such as plastics.[50] These rates of change have an autonomous dynamic and respond to the prices of inputs, but little is known about how public policy might alter the trends to enhance environmental quality.

Third, patterns of energy and materials use have been studied in relation to particular variables that may account for changes and variations in use, and some of these variables can be affected by public policy. At the household level, for example, energy use is affected by income and fuel prices, household structure and social group membership, and by individual knowledge, beliefs, and habits, as well as by the energy-using technologies that households possess.[51] Research on the determinants of consumer decisions to take advantage of technical and economic possibilities to improve energy efficiency indicates that more is required than favorable attitudes and accurate information. There is significant potential to improve residential energy efficiency with appropriately designed interventions. The research strongly suggests that the most effective interventions are specific to consumers' situations and that they use combinations of information, incentives, and social influence. Participation of affected consumers in program design can greatly increase effectiveness.[52]

Research has focused on identifying how the energy consumption patterns of firms and individuals change as a function of changes in information, incentives, technology, and social organization, thus illuminating the potential for reducing society's reliance on fossil fuels by promoting the adoption of new technologies or changing behaviors and preferences. Specific areas of extensive research include technology-focused research on energy consumption, energy efficiency, renewable energy, and nuclear power; research on price elasticities and response to incentives; and research on behavioral and informational factors affecting change in consumer choice.[53] Consumer energy choices are also shaped by political and economic structures that influence regulations and incentives for different types of energy, transportation, and housing policy, as well as the reach of advertising to different regions and social groups.

Research on energy conservation has blended behavioral and technological analyses to compare the technical potential for reducing the energy use required to provide an energy service, such as indoor climate control, with actual reductions in energy consumption. It has examined ways to achieve more of this potential reduction by identifying and removing barriers to energy conservation, such as subsidies and other market distortions, principal-agent problems, incomplete consumer knowledge and misinformation, and problems related to the early stages of the introduction of new technology. This research provides a basis for selecting promising policy options to achieve national commitments to stabilize greenhouse gas emissions.

Materials balance analysis provides the basis of an accounting system that tracks the stocks and flows of certain materials, particularly the chemical elements, through the human economy. Analysis of material flows in this fashion has been called industrial metabolism and industrial ecology.[54] As in energy research, the analysis begins with descriptive work that clarifies the principal human activities dominating each materials flow; proceeds to explorations of behavioral, economic, technological, and policy-related determinants of these activities; and expands to include prospects for changes in consumption patterns over time, including changes related to economic development.[55] One element that has been productively studied is nitrogen, which in the form of nitrous oxide acts as a greenhouse gas and affects the chemistry of stratospheric ozone and in several chemical forms plays a role in nitrogen fertilization of the biosphere. The predominant role of fertilizer production in human-induced changes to the global nitrogen cycle was only recently recognized.[56]

Our understanding of energy use is far more sophisticated than it was two decades ago. It has led to the broader concept of environmentally significant consumption and to the idea of applying analyses like those used for energy to various nonelemental materials of environmental importance, such as wood, steel, cement, glass, and plastics.[57]

An important part of research on energy use is scenario making, which seeks to extrapolate current energy use patterns into the future.[58] Time horizons of prominent scenarios range from a decade to a century. Two important goals of scenario making are transparency (explicit reviewable assumptions) and self-consistency. For global change studies, most scenarios are built on the basis of models of the evolution of national economies, often assuming a similar evolution for large groups of countries at a similar stage of economic development and structure. Typically, population growth is exogenous to the models, and per capita energy consumption is the subject of investigation. The most significant uncertainties relate to the determinants of the rate of introduction of new technologies.[59] Rarely addressed to date but presenting major sources of uncertainty are changes in preferences over time, such as those that might accompany new environmental information.[60]

Scenario making is a conservative activity in that it assumes only slow changes from established trends; it is not well suited to exploring the significance of surprises and catastrophes. Nonetheless, over the past two decades, scenario making to elucidate energy consumption has become a highly developed art, featuring dialogues among modelers to ensure quality control and inter-comparisons and to highlight debatable assumptions. Scenario building has been an essential basis for IPCC assessment models of future climate and analyses of mitigation options, the latter employing models used for scenario building in policy analysis of greenhouse gas emission control strategies.[61]

Important insights of such activities include the following:

- Estimates of future emissions of greenhouse gases are highly sensitive to assumptions about future economic, technological, and social changes, particularly about the autonomous rates of decarbonization and improvement in the energy efficiency of technology, about the likelihood of further large-scale economic transformations, and about the stability of preferences.
- Energy and materials uses are determined by multiple factors: they are not simple functions of population or economic activity but depend on complex interactions of these factors and others.

Future emissions of greenhouse gases will be driven by pressures from increasing affluence and population, with countervailing trends that reduce the amount of energy and materials used per unit of economic activity and the rate of emissions per unit of energy and materials used.

Current knowledge is inadequate to accomplish some tasks critical to understanding consumption trends, their potential environmental consequences, and the possibilities for altering them. These tasks include:

- Clarifying the determinants of "autonomous" change in energy and materials efficiency and thus improving the accuracy of projections of change in greenhouse gas emissions and in the pressure on depletable resources.

- Specifying the ways in which population, technology, affluence, preferences, policies, and other forces interact to change the rates of environmentally significant consumption in high-consuming developed economies and particularly in developing economies, where large increases in consumption are anticipated.
- Identifying and quantifying important sources of variation in the adoption of environmentally beneficial technology among firms within industries.

What Are the Human Consequences of Global Environmental Change?

Human dimensions research has made important progress in understanding the consequences of global change for people and ecosystems. Drawing on earlier research in applied climatology and natural hazards, the past 10 years have seen a major effort to understand the potential impacts of climate change on human activity, as well as studies of the impacts of past and present climate variability, the impacts of ozone depletion on human health, and the effects of land degradation and biodiversity loss on society. Credible climate impact assessments are a basis for developing policy responses to global climate change and for successful application of information on current climate variability to resource management.

Consequences of Future Climate Changes

The first studies of potential global warming impacts analyzed how crop yields and water resources would change in developed countries in response to climate scenarios of monthly changes in temperature and precipitation, based on coarse and uncertain output from climate models simulating the equilibrium response to a doubling of carbon dioxide levels in the atmosphere.[62] Later crop modeling efforts have incorporated the direct physiological effects of higher carbon dioxide levels, employed transient climate scenarios and daily data, covered developing countries, and replaced the concept of the unresponsive farmer with that of people capable of flexible adaptation to climate change.[63]

It appears that many U.S. farmers will be able to adapt to the climate changes expected from a doubling of atmospheric carbon dioxide levels by shifts in technology and crop mix but that others, especially in developing countries, will experience lower yields because they cannot afford technology and may be farming more biophysically vulnerable land.[64] Some studies of economy-wide impacts arrive at similar conclusions;[65] however, these conclusions may be sensitive to some of the assumptions underlying the analyses, as discussed in more detail in the section below on integrated assessment.

A major conceptual advance occurred in moving from impact assessments based on climate model scenarios to analyses based on an understanding of vulnerability.[66] The lack of consensus about how climate may change at the regional level, and the recognition that changes in social systems may be more important than changes in natural systems in determining the impacts of drought and other climatic shifts, reoriented the Working Group 2 of the second IPCC assessment to pay more attention to vulnerability assessment. For example, rapid increases in water demand have increased drought vulnerability, and the spread of urban settlements into coastal and flood-prone regions has increased vulnerability to sea level rise and severe storms.

Another innovation is the development of multisectoral regional assessments of the consequences of climate change. The Missouri-Illinois-Nebraska-Kansas (MINK) and Mackenzie River basin studies are good examples of a regional and cross-sectoral approach to climate impact assessment. The MINK study examined what would happen if the drought conditions of the 1930s were imposed on the economy and resources of the MINK region of the future. Taking into account adaptation, the study showed that, on the whole, agriculture would be able to cope with climate change better than forests or water resources and that impacts on the regional economy would be minor.[67] The Mackenzie River basin study examined the impacts of climate change in the Canadian Arctic using several climate and socioeconomic scenarios and including local stakeholders in defining policy questions and potential responses. The study found significant effects on northern ecosystems and hydrology.[68]

These new approaches to climate impact assessment have relevance far beyond the study of global warming. Many of the methods can be used to understand the impacts of seasonal to interannual climate variability, thus increasing the usefulness of forecasts on that timescale based on improved understanding and modeling of El Niño. The new approaches can also be used in analyzing the impacts of decadal shifts in atmospheric circulation and climate variability. For example, statistical crop models were used[69] to correlate ENSO with maize yields in Zimbabwe, and several early warning systems for famine also drive crop models with climate information to manage food security.

One of the most significant emerging areas of research is the effects of climate change and variability on human health. Several studies have shown that climate change may result in changes in the incidence and prevalence of such diseases as cholera and malaria, which debilitate human populations,[70] as well as changes in the geography of crop and livestock pests and diseases. For example, as plants have migrated upslope in the highland tropics in response to warmer climate, and tropical summit glaciers have generally retreated, and freezing levels in the mountains have moved up 150 m since 1970, mosquito-borne diseases have increasingly infested highlands and high-elevation cities such as San José, Costa Rica, and Nairobi, Kenya. Extreme events such as high temperatures have been linked to increased mortality, especially of older people and the infirm, in major cities.[71]

Important developments and insights in this general area of research include the following:

- The consequences of environmental change depend as much on the social systems that produce vulnerability as on the biophysical systems that cause environmental change.
- The consequences of environmental change are strongly dependent on the ability of people and social systems to adapt; consequently, access to economic resources is a key mediator between environmental changes and their impacts.
- Climate models can be linked to crop models to provide early warnings of famine.
- Human health may be an important area affected by climate change.

Knowledge is not yet adequate to achieve several goals critical to anticipating the likely consequences of future environmental changes, such as:

- Developing indicators of vulnerability that are sensitive to regional and social variations.
- Projecting vulnerability estimates into the future.
- Linking mesoscale outputs of climate models to regional impacts, taking into account vulnerability and the ability of vulnerable individuals and social systems to adapt.

Impacts of Past and Present Climate Variability

The most noticeable and perhaps most serious effects of long-term climate change may not be slow changes in average temperature or precipitation but rather such extreme events as storms, droughts, heat waves, floods, and wildfires; in some climate change scenarios, epidemics may be the most serious of all the dangers. Because of the importance of such episodes to society, environmental scientists are increasingly attempting to predict changes in the frequency of extreme weather events and to identify the boundary conditions for the spread of disease. Social scientists have explored the impacts of climate variability in historical and archeological studies and in research on the human impacts of climatic natural disasters. These studies have highlighted the importance of understanding vulnerability and adaptation.

Several recent studies suggest links between drought and the collapse of civilizations in Asia and Latin America. For example, the abandonment of settlements in the Andean altiplano and Amazon River basin has been shown to correlate with paleoenvironmental evidence of severe El Niño events.[72] A large body of work examines the influence of climatic variations on European and North Atlantic history,[73] showing the effects of the Little Ice Age and cooler periods associated with volcanic eruptions and the vulnerabilities of different social systems to those changes. As scientists gain new insights into paleoclimatic variability, rapid climate change, and shifts in decadal circulation patterns, social scientists can apply archeological and historical techniques to examine the human dimensions of these events.

Insights from natural hazards research also have great relevance to understanding the consequences of climate variability.[74] In the immediate aftermath of floods, hurricanes, and fires, social cohesion increases, and buildings and services tend to be restored with much greater speed than they were originally developed. Anticipatory responses, however, are more uneven, even under normal regimes of climate variability. For example, many vulnerable households and businesses fail to insure adequately against floods, even when warned of an increased near-term likelihood of flooding, and vulnerable communities often resist planning and zoning changes that would render them less vulnerable. If global climate change increases the frequency of so-called 100-year floods and other natural disasters or brings about disasters outside the range of previous experience, weaknesses in anticipatory responses will become more costly.

Researchers have begun to think about hazard response in terms of systems, recognizing that societies have always had systems for responding to the range of climatic variations, including extreme weather events, that they normally experience. For example, seasonal migration in drought-prone areas, crop diversification, hazard insurance systems, social norms of helping, flood control, fire management policies, zoning regulations, river monitoring, and other social and technological systems can alter the frequency, severity, extent, and distribution of economic losses associated with hazards. Such social systems can make as much difference in human outcomes as the distribution of weather events themselves, largely because of the effects of these systems on vulnerability.[75]

Global environmental change challenges human hazard management systems with potential major environmental surprises resulting from the nonlinear behavior of global environmental systems. Societies may be faced with rapid climate change events, ecological collapse, or epidemics that may be different in kind, faster in rate of onset, or greater in severity than the changes for which existing hazard management systems are prepared. We do not know how societies may alter their hazard management systems to face the prospect of such environmental surprises. However, studies of environmental risk management and decision making show that changing practices in anticipation of high-consequence/low-probability events poses a major challenge: democratic societies typically have great difficulty reaching consensus on policies to manage these sorts of environmental risks and even in arriving at widely shared understanding of them.[76]

Hazards research has also shown the potential value of understanding the consequences of El Niño and other potentially predictable aspects of seasonal to interannual climate. Several studies have linked El Niño events to major disaster losses in such regions as Northeast Brazil, Australia, and Southern Africa, and insights from these studies can contribute to applications of improved predictions of climatic conditions. For example, the correlations between crop yields and droughts associated with El Niño indicate the potential value of forecasts to food security.[77]

Important insights and findings from this area of research thus include the following: the vulnerability of a society and of its hazard management systems is often more important than the magnitude of a climatic event in determining impacts on people, and past climatic variations may have been associated with large-scale abandonment of human settlements and major migrations. More information is needed about the following issues: the consequences of newly identified rapid climate changes of the past and the ability of hazard and resource management institutions to respond to surprising shifts in climate and to seasonal forecasts.

Ozone Depletion

The main reason for widespread concern about low Antarctic ozone levels, and an important stimulus for policies to eliminate ozone-depleting chemicals, has been the concern that declines in stratospheric ozone could affect human health by increasing skin cancer, causing eye problems, and stressing immune systems. Considerable research has been directed to better understanding the links between ozone depletion and human health, as well as possible impacts on ecosystems. Most of the research to date consists of epidemiological and medical studies on the effects of increased ultraviolet (UV) radiation.

Considerable progress has been made in understanding the links between UV exposure and skin cancer, and investigating the still-controversial link of UV exposure to cataracts.[78] Additional research is needed to accomplish several critical goals: to examine the effects of ozone depletion on animal populations and ecosystems of economic or other societal value, to understand behavioral and demographic aspects of UV exposure, and to link trends in industrial use of ozone-depleting chemicals to risks for human health and ecosystems.

Environmental Change and Security

Another set of studies has examined the ways in which global change may lead to conflict, mass migration, or threats to national security. This research tends to build on studies of deforestation and climate impacts that suggest that environmental change may cause competition over resources, refugee migration, or political unrest. For example, it has been suggested that environmental degradation in developing countries has resulted and may again result in violent conflicts.[79] It has also been discussed how climate change may create conflict over international water resources and may destabilize food security.[80] A new IHDP project sets out to examine the relationship between global change and security from global to local scales.

This research focus has achieved one important end: highlighting the plausibility of several types of potential impacts of global environmental change on conflict and security. More research is needed to accomplish a related goal: providing careful empirical analysis of the relative roles of environmental change and other factors affecting conflict and migration.

What Are the Potential Human Responses to Global Change?

It is difficult to separate conceptually the causes and impacts of global change from responses to it because in many cases responses to environmental change immediately modify the causes and the impacts. For example, the adaptive responses of farmers to drought have shown how hazard warning systems moderate disaster losses. Studies have examined human responses to global change at the individual, community, national, and international levels. This section reviews progress in several pertinent areas of research, including international environmental policy, local and regional institutions, decision making and risk analysis, and valuation. We also examine progress in "integrated assessment" of global environmental changes.

International Environmental Policy

Much of the work on global-level international policy and institutions has focused on the development and implementation of regulatory "regimes" established through transnational, regional, and international agreements, such as the Montreal Protocol, the Climate Change Treaty, and the Biodiversity Treaty. These studies draw on work on the theory of international regimes, bargaining, and the structural and institutional conditions supporting international cooperation.[81] They have built the beginnings of a useful body of data and identified suggestive empirical regularities, although they have not yet supported rigorous testing of hypotheses. More specifically, these studies have focused on regime formation, the modes of influence of international environmental institutions, the use of financial transfers for international environmental protection, long-term comparative national and international policy development, the implementation of international environmental agreements, the analogy between international environmental protection and local management of common-property resources, and the systems for monitoring and enforcing compliance.[82]

A significant body of research on policy instruments at the national and subnational levels is highly relevant to implementing international environmental agreements. This research has led to improved understanding of the strengths and limitations of strategies such as regulation, various classes of financial incentives and penalties, liability law, provision of information, inducements for technological development, disaster prevention and preparedness, and alterations in the structure of markets for mitigating and responding to global change.[83]

The following are some important findings and insights of this research domain:

- Several systematic difficulties exist in changing the behavior of specific targeted nation states, even when policies are backed up with financial resources.[84]
- Policy is often strongly path dependent in that early decisions may constrain or determine later ones, thus making discussion of alternative policies extremely difficult at later stages.[85]
- Transnational networks of scientists can play a strong role in early definition and framing of an issue, although they have only limited ability to motivate international agreement or to influence the interpretation of scientific knowledge by political decision makers.[86]
- Assessment of risks and response options tends to follow, rather than lead, political target setting, and the range of options tends to contract over time.[87]
- Coercive sanctions have limited effectiveness in enforcing compliance, compared with carefully designed, linked systems involving rule design, information provision, granting of capacity and legal authority to selected actors, and transparent processes of implementation distributed among multiple formal and informal institutions.[88]

Knowledge is not yet adequate to achieve the following:

- Identify specific combinations of policy instruments and monitoring strategies that will induce a broad range of actors to behave in ways that lead to achieving internationally agreed-upon goals.
- Identify specific international and national institutions that can effectively link the international, national, and local levels and make it possible to design effective and acceptable policies.

National and Local Institutions

Human responses to global environmental change are shaped by institutions, defined broadly as the norms, regulations, interpretations or understandings, and social organizations that bear on a particular activity. The past decade has seen a renaissance of research on the structure and dynamics of social institutions and a change in thinking about how these institutions shape human activity.[89] This work is being applied increasingly to problems of institutional design for managing environmental change.[90] It is developing a knowledge base on how social institutions have succeeded and failed at long-term management of environmental resources that will be useful for informing future environmental policy choices.

The fundamental issue for environmental management is that of designing incentive-compatible institutions.[91] Such institutions are capable of internalizing, within individual households, private firms, and public organizations, the costs of the negative effects of human activities, effects such as pollution, when they are not otherwise penalized by the market. These so-called externalities are a major source of environmental stress. Even if accurate measurement is developed of the costs of externalities, the question remains of how to design institutions to avoid generating these negative effects. At present we are better at dealing with emissions and other externalities after the fact than at preventive institutional design.

An important focus of recent research on national and local institutions is property rights institutions, as they bear on the management of environmental resources.[92] One advance has been to demonstrate the ambiguity of such terms as "the commons" and "common property" and hence the need to specify property rights arrangements in more detail.[93] The term "common property" has been used to signify, at one extreme, unregulated open-access situations, as in many high-seas fisheries, frontier agricultural or mining development, and air and water pollution. At the other extreme, it has referred to highly regulated and tightly circumscribed systems governing the use of land or natural resources as found in some communities, where "commons" signifies a viable institution of collective rights and responsibilities.[94] Most "common property" institutional arrangements are somewhere in between.

Research has increasingly focused on alternatives to top-down government control over commons situations, alternatives such as collective action on the part of resource users, and market-based systems of allocation. Attention has been redirected to questions about external and internal conditions under which collective action can prevent or mitigate environmental problems. This line of research has produced significant insights, showing, for example, that common-pool resources are not inevitably destroyed by human overexploitation as presumed in the model of the tragedy of the commons. Rather, the fate of these resource pools depends on the formal and informal institutions that monitor their condition and control their use.

Comparative case studies and game theory experiments show the importance of time, scale, and socioeconomic structure to the success of collective action, and they show the need for local institutions to establish good systems of monitoring, communication, and normative control of behavior.[95] They also show the importance of appropriately structured linkages between local organizations, which tend to have more detailed knowledge about resources, and higher-level organizations, which can enforce access rules and address externalities beyond the locality.[96] These findings bear on questions of institutional reform and innovation, suggesting as they do some advantages of more decentralized management regimes.

Important advances in the knowledge of institutions include the following:

- The discovery that common-pool resources have sometimes been managed sustainably by societies for periods of several centuries.
- The development of a typology of institutions for managing common-pool resources (particularly property rights institutions).

- The development of the beginnings of a body of knowledge about how particular institutional types can effectively sustain resources.
- Recognition of the importance of locally based and self-organized institutions for monitoring and controlling resource use.
- Recognition of the ways that higher-level institutions can constrain and enable local ones.

Knowledge is not yet adequate to match particular institutional types appropriately to resource types and social settings or to identify effective ways of linking institutions across levels to maintain particular resource types.

Market Mechanisms

Property rights research also has led to research on market-based policies. Recognizing that in many situations neither local-level management nor command-and-control solutions may be effective or feasible, researchers have focused on the use of exclusive tradeable property rights or privileges in environmental management.[97] In marine fisheries, long plagued with open-access problems, individual transferable quotas have become increasingly popular. Research shows some economic benefits but mixed results with regard to creating incentives for conservation.[98] Emissions trading has been shown to reduce the costs of regulation.[99] Experiments have been under way to apply this idea internationally, for example, by using international carbon emissions offsets to help developing countries finance environmental regulation.[100] Distributional effects of trading are major issues for both fisheries and emissions regulation.

Research on modifying the ways in which markets allocate environmental resources has significant insights to offer in responding to global change. Some of this work is based on estimating the full social value of an environmental resource and instituting taxes or other financial incentives to bring the resource's price into line with its social costs. Important advances in the area of market mechanisms include indications that market-based policies (e.g., transferable quotas, emissions trading) have significant cost advantages in theory and in some applications and recognition that the effects of these policies are situation dependent. Knowledge is not yet adequate to meet several critical needs for understanding how market mechanisms would work in practice, such as estimating distributional effects of particular market-based policies and matching market-based policies to resources and social and political conditions for optimal effectiveness.

Valuation of Responses to Global Change

Responses to global change require that decision makers face important questions of resource allocation: How can decisions appropriately take into account the value of resources that have no market price? How do and how should societies allocate resources between present and future generations? How do and how should societies decide equity issues within the present generation?

Many studies use forms of cost-benefit analysis to compare the costs and benefits of various responses to global change. In these studies the economic costs of impacts as well as responses are usually included. The results of cost-benefit analyses tend to be highly sensitive to assumptions about nonmarket values, such as those of ecological services like water purification and crop pollination, human health and life, and prevention of species extinctions. Considerable effort has recently been devoted to approaches for evaluating nonmarket values by various "indirect market" methods, such as measuring the cost of activities engaged in to compensate for the effects of pollution and "hedonic pricing" (e.g., estimating the amount of increased compensation offered workers for more hazardous jobs). Each of these methods has been applied to a restricted class of nonmarket values, and each has certain clear limitations.[101] Partly to overcome the limitations of indirect market approaches, economists have increasingly turned to contingent valuation methods, in which individuals are asked directly to express their willingness to pay for particular environmental improvements. This technique has found some acceptance in policy circles, but methodological and conceptual questions about the approach are still being hotly debated.[102] Some progress has also been made in estimating the nonmarket value of environmental resources for inclusion in national income accounts.[103]

Researchers have also examined the use of novel methods for integrating disparate kinds of values without converting them to monetary units. Techniques of multiattribute utility analysis allow values to be integrated in various ways to reflect users' value priorities.[104] Simulations and policy-exercise studies clarify key uncertainties, values, and interactions, and deliberative methods involve both experts and nonexperts in interpreting analyses.[105] Such experiments promise to yield methods that complement economic techniques of valuation, where the latter give incomplete or inconclusive results.

There also have been efforts to deal analytically with the obligation of the present generation to future generations. For example, a choice not to mitigate climate change benefits the current generation but imposes unknown adaptation costs on future generations. These analyses are highly sensitive to the discount rate used to represent tradeoffs between present and future resources. Critics of conventional cost-benefit analysis often insist that the discount rate approach results in a dictatorship of the present over the future. The issue of how to take into account obligations of the present toward the future and the problem of intergenerational income distribution both remain unresolved. Ethical analyses and discussions of these issues remain more unsatisfactory than economic analyses; however, scientific debate remains contentious.[106] Analytical techniques are also being developed to address equity issues in the present generation.[107]

This field of investigation is in a highly vigorous state. For its results to have satisfactory practical value, analysis must develop to the point at which it can give confidence in the validity of particular analytical techniques for estimating nonmarket values and provide a satisfactory way of analyzing equity issues, particularly those relating to intergenerational equity.

Understanding Risk, Uncertainty, and Complex Choices

Responding to the prospect of global change requires interventions in complex systems that are not fully understood. Decision makers can benefit from recent advances in understanding human judgment and decision processes regarding complex environmental choices. Over the past decade this research has increasingly clarified why scientific efforts to analyze and assess global environmental threats do not easily lead to social consensus on policy responses to those threats. This research shows that, while analyses normally focus on a few critical outcomes, such as sea level rise or species extinction, nonexperts commonly consider multiple dimensions of environmental conditions and decisions, such as risks to human health, economic costs and benefits, the extent of scientific uncertainty and ignorance, catastrophic potential, and threats to aspects of the environment with intrinsic value. Moreover, even single dimensions such as human health are multifaceted; people assess risks partly depending on whether they believe they can control personal exposure and their own emotional responses to the specific hazard.[108] The factors that matter most to people can vary with the situation and with their social position, and these differences then influence their policy preferences.[109]

These findings have implications for scientific choices and the policy process. Chief among them is the idea that the information that results from science-driven research agendas is not necessarily considered useful or relevant by those whose decisions the scientific analysis is intended to inform. For scientists to know what information will be considered useful and relevant, they must have input from those who participate in environmental decisions. Each technique used to assess environmental risks inevitably makes judgments about what the problem is that needs scientific input, which dimensions of the problem should be investigated, and their relative importance.[110] Consequently, decisions that rely on any particular analytical technique are often rejected by people who do not accept its underlying judgments. Moreover, decisions made without the participation of some of the interested and affected parties tend to be rejected by those parties. Consequently, decision processes that are too narrowly based, either in terms of analysis or participation, often fail to meet decision makers' needs for information and involvement.[111]

The ability to reach an implementable decision depends on the process that combines analysis and deliberation to frame scientific questions, gather and interpret information, and present it to participants in the decision in ways that address their needs for information and understanding. The critical elements of this decision process and some important related research questions have been identified.[112] The decision process is also a major concern of the new National Center for Environmental Decision-Making Research, established by NSF. Additionally, research has begun to illuminate how scientific and technical information is incorporated into environmental decision making at local, national, and international levels.[113]

A number of important findings have been made in this research area:

- Whereas many risk assessments consider only a few dimensions of risk (e.g., mortality risk, economic loss), nonspecialists' judgments about risk typically consider multiple dimensions.
- Objections to the results of risk assessments often arise from disagreement about judgments underlying the assessments or from restricted participation in making those judgments.
- The adequacy and acceptability of a judgment about risk depend on both the underlying analysis and the deliberative process that judged which analysis to do, how to collect information, and how to interpret it.

Knowledge is not yet adequate in this field to accomplish several essential tasks, such as:

- Adequately characterizing uncertainties and scientific disagreements about the nature and extent of risks.
- Designing processes that combine analysis and deliberation to ensure that information is developed and organized to meet the needs of the range of decision participants.
- Structuring procedures that inform scientists' work and decision makers' understanding with a combination of formal analysis and the information, perspectives, and judgments of others involved in risk decision making.

Integrated Assessment

One approach used to understand the implications of policy responses to global change is known as "integrated assessment." In integrated assessment, methods or processes are applied to combine knowledge from multiple domains, such as socioeconomic and biophysical fields, within a consistent framework to inform policy and decision making. Integrated assessments of environmental issues have been conducted since the 1970s,[114] but the past 10 years have seen a flood of interest and activity, particularly to address global climate change. Since 1990 the number of integrated assessment projects relating to climate change has grown from only a few to more than 40.[115]

Although the concept of integration has been very broadly applied with regard to what is integrated and how, recent practice in the area of climate change has been rather narrow. Integration can mean "end-to-end" connection of a causal chain from fossil fuel emissions and land use to their impacts, with weighing of climate change impacts against measures to reduce them or to adapt. (Some amount of such "vertical" integration is often taken as a requirement for integrated assessment.) Integration can also denote expanding each link of this chain to consider more diverse source activities and emissions, more atmospheric and biotic processes, more forms and sectors of impacts, or more spatial detail or heterogeneity of agents. Integrated assessments may also examine social and biophysical linkages between climate change and other issues (e.g., ozone depletion, tropospheric air pollution) or include linkages to other social or policy issues such as public health or economic development. In addition to formal modeling, methods for integration can also include structured cross-disciplinary discourse; judgmental integration of data, theory, and formal models from separate domains; and structured heuristic processes such as simulations, scenario exercises, and policy exercises.

A major purpose of integrated assessment is to provide a consistent framework for the representation, propagation, analysis, and communication of uncertainties. A striking result of the few attempts to integrate uncertainty quantitatively across biophysical and socioeconomic domains has been that, among the various kinds of uncertainties, socioeconomic uncertainties appear to predominate in assessing aggregate impacts and net benefits of policies and decisions. Key socioeconomic uncertainties include future population growth and migration, social and political determinants of environmentally relevant consumption, rate and character of technological change, adaptation-mediated regional impacts of climate and environmental change, effects of policies, and variation in preferences.

For example, in an early assessment that integrated energy-economic and carbon-cycle models, it was found that the largest contribution to uncertainty in atmospheric CO_2 concentrations at the end of the next century came from estimates of the ease of substitution of fossil and nonfossil energy inputs in the economy and general productivity growth;[116] uncertainty in the airborne CO_2 fraction and in total fossil fuel resources ranked near the bottom of all contributions to uncertainty. In 1993 and 1996, studies using a stochastic integrated-assessment model found that differences in preferences dominated climate uncertainty in determining preferred policy choice.[117]

Recent integrated climate assessment, however, has stressed vertical, or end-to-end, integration, primarily by building single integrating computer models. These models typically combine and modify preexisting models of energy and the economy, atmospheric chemistry and dynamics, oceans, the terrestrial biosphere, and/or agriculture and other forms of land use. In each project some domains are represented richly, others very schematically. Most integrated assessment projects have a national to global scale, rather coarse spatial and sectoral resolution, and weak representation of policies and political processes.

Early work on integrated assessment of climate change combined energy-economic models with either accounting or input-output systems to develop comprehensive emissions scenarios or with simple highly parameterized atmospheric models to project the effect of specific economic and control scenarios on atmospheric trace gas concentrations.[118] More recent projects have added climate and impacts modules.

Projects differ in their conceptual emphasis and the potential insights they can offer. Some concentrate on the dynamics of emissions, atmospheric accumulation, impacts, and responses. These projects postulate a single global optimizing producer-consumer and require a common metric for abatement costs and climate damages, so they normally represent regional or global climate damages by simple aggregate functions of temperature change. These models allow the investigation of dynamically optimal abatement strategies that balance, over time, the costs of emissions abatement and damages from climate change or that meet a specified environmental target at minimum cost. They also permit study of how preferred policies depend on alternative specifications of damage functions, discount rates, the dynamics of impacts and technological change, or the structure of world regions and of bargaining.[119]

Other integrated assessment projects concentrate on the specification and propagation of uncertainty, allowing identification and ranking of key policy-relevant uncertainties or the elaboration of adaptive and learning strategies for responding to progressively resolved uncertainty over time.[120] Still other projects concentrate on the elaboration of spatial and sectoral detail for climate impacts, human adaptation and responses, and human-mediated feedbacks through land use change to the climate system.[121]

Integrated assessment practitioners have claimed insights such as the following: that a large near-term abatement effort for climate change is not justified; that the market impacts of climate change in high-income countries (but not low-income ones) will be small; that optimal abatement paths would reduce gross domestic product by only a few percent, compared with unconstrained paths, and can be accomplished with carbon taxes of a few dollars per ton; and that delays of a few decades in controlling emissions are preferable to immediate action, even if stringent reductions are subsequently determined to be needed.[122] These conclusions, however, depend on several particular characteristics of most assessment models: they offer very limited representation of the possibility of extreme events; they only reference doubled CO_2 scenarios and so fail to include the concentrations likely by the end of the next century under aggressive fossil fuel growth, which drives atmospheric, ecosystem, and impacts models all far out of their validated ranges; they include weak or no representation of multiple interacting environmental stresses; and they assume limited learning in technological change or policy.

Important advances in knowledge from integrated assessment modeling include the following:

- The finding that socioeconomic uncertainties dominate biophysical uncertainties in contributing to aggregate uncertainty about future climate impacts and preferable response strategies.[123]
- Initial quantitative estimates of the benefits available from various levels of international cooperation to manage climate change.
- An evaluation of the implications of sulfate aerosols in climate change for alternative abatement strategies.
- A preliminary characterization of the effects of linked demographic, economic, and climatic pressures on land cover and atmosphere.[124]

Knowledge is not yet adequate in this field to achieve the following:

- Reduce major socioeconomic uncertainties in integrated assessment models.
- Estimate impacts and preferable policies from models that relax some of the most important restrictive assumptions of existing models (e.g., doubling of CO_2 concentrations).
- Provide acceptable techniques for choosing among model simplifications, so that outputs best meet users' needs.

What Are the Underlying Social Processes, or Driving Forces, Behind the Human Relationship to the Global Environment?

Human dimensions research has also examined fundamental questions about the broader political, social, technological, and economic forces that shape the human activities that cause environmental change and influence its consequences. The number of such forces that may directly or indirectly alter the global environment has no limit. This section focuses on several driving forces about which important scientific progress has been made and which are often mentioned as arenas for policies to mitigate environmental change. There are many other important social forces and phenomena whose direct or indirect environmental effects may also be large and that may also have policy significance. These include national taxation policies, economic inequality within and between countries, war and the international arms trade, and societies' treatment of women. Important scientific progress has been made in understanding how humans perceive global change; the ways that individuals and institutions cope with environmental changes; and the dynamics of human populations, technological change, and economic transformations.

Public Attitudes and Values

Public support is necessary for any collective response to global environmental threats, whether through policy decisions or the aggregated actions of large numbers of individuals and organizations. A series of studies shows strong and persistent concern and support for environmental quality and protection in a variety of countries, rich and poor;[125] in the United States and other countries where relevant data are available, this support cuts across socioeconomic lines. In some developed countries, concern is strongly correlated with education; in some it is strongest in younger age cohorts. Concern about global environmental problems relative to local and national ones is strongest in developed countries, whereas in countries with highly visible pollution problems, environmental issues closer to home are seen as relatively more serious.[126] Environmental concern is strongest in countries with serious objective pollution problems and in countries with strong environmentalist values.[127]

Research on the factors underlying environmental concern finds that it is partly rooted in basic psychological values, particularly concerns with the welfare of others and of future generations and a widespread belief in the sacredness of nature.[128] This work draws on extensive basic research that has developed a comprehensive typology of human values.[129] Additionally, environmental concern reflects beliefs about how environmental conditions may affect those things that an individual values, suggesting that public response to newly identified environmental conditions may depend on the kinds of consequences projected for those conditions.[130] Despite some widely held misconceptions about the causes of climate change,[131] such variation from accepted scientific accounts does not seem to diminish levels of public concern with the environmental problems that also concern scientists.

The other side of the coin of environmental concern is an apparent unconcern by individuals about the environment, as reflected in increasing levels of materials and energy consumption associated with increased income. Critics of "consumer society" point to advertising and the mass media as drivers of materialist attitudes and desires and argue that these forces and others are driving the emerging middle classes in many developing countries to emulate North American styles of consumption. These plausible arguments have not yet been supported by careful quantitative studies of the relevant social forces, attitudes, and behaviors.[132]

Important advances in knowledge in this area are documentation of widespread support for environmental protection across countries and socioeconomic groups and initial identification of the ways that values, beliefs, and attitudes affect political support for environmental policy. Knowledge is not yet adequate to relate the development of public attitudes to mass media coverage of environmental issues and the roles of elites, interest groups, advertising, and social movement organizations and to model the development of public support for action on emerging global environmental issues as a function of new scientific knowledge.

Individual and Household Behavior

Household consumption of energy and certain materials is important both in causing and in responding to global change. Consumer behavior is determined partly by values, attitudes, and beliefs but is strongly mediated by nonattitudinal factors, including the cost and inconvenience of making environmentally significant behavioral changes, the availability of relevant technologies, institutional barriers, knowledge about which behaviors are effective, and the presence or absence of supporting public policies and social pressures. Consequently, the determinants of consumption are highly situation specific, and efforts to change the environmentally relevant consumption of households require multifaceted approaches that identify and address the barriers to change that are most important for the specific behavioral change and target actor.[133] Considerable progress has been made in understanding certain key classes of consumption, such as residential energy use in some high-income countries. A major research challenge, only now beginning to be addressed, is to understand how the factors that drive such consumption vary with national and cultural context.

Political behavior is also important to responses to global change. As in the case of consumption, the connections between individual concerns and political influence are complex and imperfect. Political action reflects opportunities for effective political participation individually and through environmental organizations, changing value priorities, the framing of issues in the mass media and by interested parties, and the actions of scientific experts individually and through epistemic communities.[134] Research linking environmental attitudes to political participation and influence is helping build understanding of the political feasibility of policies to meet international commitments.

Important advances in knowledge of individual and household behavior include the following:

- Improved understanding of the many factors affecting specific types of environmentally significant consumption at the household level (especially energy use) in high-income countries and recognition of the situation specificity of these effects.
- Recognition of the various factors affecting individuals' political behavior on environmental issues.
- Appreciation of the need for multifaceted approaches in policies aimed at altering consumption patterns.

Knowledge is not yet adequate to achieve several ends:

- Project environmentally significant consumption in developing countries as a function of economic, demographic, and other changes.
- Model the causes and trajectories of environmentally significant household consumption other than energy.
- Develop more realistic assessments of likely environmental policy outcomes that take behavioral responses into account.

Economic Transformations

Various large-scale economic transformations around the world may have major implications for the generation of environmental change and for human vulnerability to it. These transformations include the dependence of an increasing proportion of the world's population on global markets for necessities such as food and fuel that were previously produced locally, much of them outside the money economy; increasing liberalization of international trade;[135] the emergence of service economies in place of manufacturing-based ones in most high-income countries; and the transformation of formerly socialist economies from a central command model to a more decentralized market-based one.

One of the most important themes in the past 10 years of social science research has been the "globalization" of economies and cultures.[136] The increasing mobility of capital and labor has facilitated the expansion of transnational corporations and massively restructured the geography of industry, agriculture, human settlements, and all of their associated environmental impacts.[137]

The environmental effects of trade liberalization are more complex than sometimes realized. Despite claims that trade liberalization has predictably negative environmental impacts, the limited existing evidence suggests that environmental impacts are sometimes positive (e.g., better allocation of soil and water resources in agriculture) and sometimes negative (e.g., foreign investment in countries with lax environmental regulations). Analyses of overall impacts must consider the effects on resource allocation, the scale of overall economic activity, the composition of output (e.g., manufacturing vs. services), effects on developing "green" technologies, and the interactions of trade with policy.[138]

The North American Free Trade Agreement (NAFTA) stimulated some important work on the environmental implications of changing trading regimes. Although some scholars claimed that NAFTA would result in improved environmental conditions, especially in Mexico, others suggested that free trade would result in environmental degradation as communities relaxed regulations to attract industry or as polluting industries moved to Mexico to take advantage of lower wage rates.[139] NAFTA was also predicted to alter agricultural production patterns in ways that would increase Mexico's vulnerability to U.S. droughts.[140]

Perhaps the most important and dramatic change in the global political economy in the past 10 years is the collapse of the Soviet bloc and the transformation of Eastern European economies. These economies had previously been among the most energy and pollution intensive in the world. Studies showed that in the immediate aftermath of political changes in such countries as Russia and Poland, greenhouse gas emissions decreased as industrial production and consumption fell in the ensuing economic crisis.[141] Now, as foreign investment and privatization transform these economies, the implications for the global environment in terms of emissions, land use, and resource management are unclear.

Important advances have been made in understanding the effects of economic transformations:

- Most of the world's food is now produced within a global system, in which most of the basic grain on the world market is produced in very few countries. The fact that many countries depend on food imports greatly enhances the regional and global impacts of climatic change and variation in those grain-producing regions on which much of the world depends.
- Industrial production is shifting from core industrial countries to the developing world.
- The service sector has grown dramatically, especially in urban areas, contributing to increased vulnerability of human settlements, as poor people move into cities for work and must often live in hazard-prone environments.

Knowledge is still inadequate for several needs:

- Establishing the theoretical and empirical links among economic globalization, global environmental change, and the consequences of global change.
- Estimating the net overall and regional environmental effects of trade liberalization.
- Estimating the likely long-term environmental effects of ongoing economic transformation in the former socialist bloc.

Human Population Dynamics

The past decade has seen substantial progress in understanding fundamental population processes: fertility, mortality, and migration as well as the relationships among them that determine population growth, age structure, and geographic distribution. This research is important to global change because population dynamics are some of the most important driving forces behind land use change and energy use and a factor in increasing demands for food, water, and living space that increase vulnerability. Efforts to reduce fertility (i.e., the number of births per woman) have received the most research and policy attention, with Asia, the Middle East, Africa, and Latin America being the areas of interest.

Based on evidence from censuses, the World Fertility Survey, the Demographic and Health Surveys, and other surveys, it is now conclusive that fertility rates have dropped in a sufficient number of formerly high-fertility countries to produce substantial reductions in the world's fertility. The world's total fertility rate has dropped to approximately 3.0 today—thus having achieved most of the reductions needed to reach replacement-level fertility. The Middle East and sub-Saharan Africa are still the regions with the highest levels of fertility, but even there evidence is emerging that fertility reductions have begun.

Considerable research has examined the causes of this fertility decline. Almost all countries that have achieved substantial fertility declines in the past 25 years have had concerted family planning programs. The effectiveness of these programs in reducing fertility levels, as opposed to other factors, such as rising education levels, has been rigorously debated.[142] Most agree that family planning programs have been one of many factors leading to fertility decline; the disagreement revolves around the size of the family planning program's effect.

With respect to mortality, most reductions in the past were attributable to declines in infant and child mortality. That trend is now shifting, and attention has been turning to questions of how long people might live. The debate on the limits has not been resolved,[143] but the research fueling the debate has helped to increase our focus on morbidity associated with increasing longevity and the need to have global change research include the effects of increased longevity.

Human migration is an issue of emerging importance for global change because of the possible environmental impacts of concentrated populations and the vulnerability of these populations to extreme events, especially when people are concentrated in coastal zones or floodplains.[144] Research progress in understanding migration has been hampered because accurate data are hard to acquire, and when they can be collected, they tend to be aggregated.

Finally, household size has been declining in a number of countries as affluence increases. For example, in the United States the proportion of all households with just one or two members increased from 46 percent in 1970 to 57 percent in 1995. Since households have effects on the environment from production and consumption that are somewhat independent of the number of household members, models should consider both population growth and growth in the number of households. Important findings in human population dynamics include the following two fundamental ones:

- Total fertility rates are declining worldwide, particularly in countries that have had concerted family planning programs.
- Human migration, particularly urbanization and movement to vulnerable environments, has been identified as a major potential influence on future environmental change.

Knowledge is not yet adequate to estimate the environmental effects of particular types of migration or to model environmental impacts as a function of household size and composition as distinct from population effects.

Technological Change

A major source of uncertainty in projecting future human contributions to global change and analyzing response costs is the rate at which improved technology will lead to the substitution of abundant natural resources for scarce ones and of reproducible capital for depletable resources. Economists and technologists have typically viewed technical change as widening the possibility of substitution among resources. This has frequently led to a bias in favor of assuming adaptation strategies for response rather than mitigation strategies. Ecologists and other biologists have typically regarded substitutability as being narrowly restricted. The argument about biodiversity is, in part, a reflection of these alternative views. The problem has not yet been modeled satisfactorily, nor has sufficient empirical research been conducted to test the alternative perspectives. However, dialogue between the two theoretical camps is increasing and signs of a conceptual synthesis are beginning to appear, in which the questions are formulated in terms of the relationship between rates of substitution and rates of resource consumption.[145]

Past research has documented some regularities in the time path of change in environmentally significant technologies, including rates of technology diffusion and secular trends toward so-called dematerialization and decarbonization; it has also documented variations around general time trends.[146] There has been a lively empirically based debate about the extent to which scarcity may induce innovations that reduce costs and find substitutes, a debate that may be heading toward synthesis.[147] Extensive studies have also been conducted of the conditions favoring adoption of technological innovations. This research is starting to make it possible for modelers of global change effects and builders of integrated assessment models to replace ad hoc coefficients of technological change with numbers based on empirical analysis and sound theory.

Important advances in this field include the following: identification of secular trends toward dematerialization and decarbonization of economies, along with variations around these trends; identification of factors influencing the rates of adoption of technological innovations; and identification of the substitution rate of inexhaustible resources for depletable ones as a key parameter for studies of sustainability.

Knowledge is not yet adequate to model the factors influencing variations in average rates of decline in national energy intensity and related indicators and variations around the average among industries and firms or to model the effects of environmental policies on rates of innovation in environmentally benign technologies.

LESSONS LEARNED

Human dimensions research has produced a large number of advances in knowledge about global change, as the previous section indicated in some detail. In general, recent research has refined earlier understanding of human-environment interactions in ways that will enable more accurate modeling and anticipation of global change and its impacts and better-informed policy responses. Many of the major advances in knowledge can be summarized in a few major categories.

Relative Importance of Socioeconomic Uncertainty

Several analyses clearly indicate that socioeconomic uncertainties dominate biophysical uncertainties in assessing future climate impacts. Because of the great significance to the future of environmental change of such phenomena as rates of economic growth and adoption of environmental technology, which can only be forecast with great uncertainty, relatively small improvements in our understanding of these phenomena can significantly improve the ability to anticipate and respond to the effects of climate change. The same reasoning may apply to ecological changes, the rates of which are also sensitive to socioeconomic factors, such as human demands for land and water, the long-term forecasts of which are highly uncertain.

Complex Determination of Environmentally Significant Consumption

The term "consumption" has different meanings in different scientific disciplines; research on environmentally significant consumption focuses on human activities, such as clearing forests and using fossil energy, that transform or degrade biophysical resources and thus affect things that people value. Accumulating evidence indicates that all of the environmentally significant kinds of consumption are determined by multiple factors, including such driving forces as population growth, economic and technological development, cultural forces, values and beliefs, political activity, institutions, and policies and by the interactions of these forces. Research shows that the interactions are typically specific to the type of consumption, the responsible decision maker, and the geographic and sociopolitical context. Studies are illuminating the operations of the driving forces as they affect particular types of consumption (energy, forest clearing) in particular contexts.

Human dimensions research is also advancing our understanding of some of the driving forces. It has documented the widespread global support for environmental protection and some of the reasons for that support, the many factors influencing environmentally significant consumption by individuals and households, the trend toward globalization of trade in environmentally significant goods and services, the increasing importance of human population migrations as an environmental threat, and the environmental significance of major technological trends affecting the rates of substitution of inexhaustible resources for depletable ones.

Importance of Vulnerability Analysis in Impact Assessment

Research on the impacts of past climatic variability on societies and economies shows that these impacts depend as much on the social systems that produce vulnerability as on the biophysical systems that cause environmental change. Vulnerability depends on a number of factors, including intensity of land and water use and population immigration in marginal areas, access to economic resources, infrastructure for hazard response, the health status of potentially affected populations, and the structure of the hazard management systems a society has in place to prepare for and manage environmental events. Vulnerability analyses are essential for estimating the human impacts of environmental change and variation. For instance, climate models can be linked to crop models and estimates of vulnerability to provide early warnings of famine, and ecological models can be linked to vulnerability analyses to estimate the effects of global change and climate variability on human health.

Importance of Institutional Design to Environmental Resource Management

Research on human use of common-pool resources has shown that the "tragedy of the commons" scenario is not inevitable. Tragedy has often been prevented and resources sustained over periods of generations to centuries by the design of institutions that monitor the conditions of resources locally, effectively govern access to them, establish norms of resource use and sanctions for overexploitation, and appropriately link local institutions with those at higher levels. A key to implementing effective responses to global change is to design incentive-compatible institutions, that is, institutions capable of internalizing the overall costs of environmental degradation for the individuals, private firms, and public organizations whose actions create environmental stress. Ongoing research on existing institutions and on the theory of institutional design is clarifying the conditions for successful long-term environmental resource management and the institutional structures that have been successful with particular types of resources. Better understanding of institutions that shape human interactions with the environment, these institutions' functioning, and their linkages is essential to forecasting global change and developing policy responses that reduce vulnerability as well as to effective long-term resource management.

Importance of Both Analysis and Deliberative Procedure in Environmental Decision Making

Wise environmental policy making requires good analyses of the various kinds of values and costs associated with environmental change and of the values and costs associated with available policy options. Human dimensions researchers are developing and refining analytical procedures for environmental accounting and valuation, cost-benefit analysis, and other tools to estimate the costs of global change and of policy response options. However, research also shows the dependence of these analyses on highly contestable judgments in areas where knowledge is incomplete and where value disagreements are significant, such as in estimating nonmarket values and intergenerational equity. One lesson is that, in addition to reliable analytical procedures, wise decision making depends on developing appropriate and acceptable processes for deliberating about analytical assumptions and identifying information needs among scientists, policy makers, and others interested in global change decisions. Research on the effectiveness of various deliberative procedures is in its infancy compared with research on analytical techniques.

Importance of a Broad-Based Infrastructure

A broad national and international infrastructure is developing for research and policy development on the human dimensions of global environmental change. Within the USGCRP the effort has broadened from a program of investigator-initiated studies funded by NSF to encompass some larger and more focused NSF initiatives, such as a set of human dimensions centers and teams and efforts on policy research and global change and on methods and models for integrated assessment; significant research activities by the U.S. Department of Energy (DOE) and its laboratories, the U.S. Environmental Protection Agency (EPA), the National Oceanic and Atmospheric Administration (NOAA), and the National Institutes of Health; smaller research programs at NASA, the U.S. Department of Agriculture, the U.S. Department of the Interior (DOI), and the National Institute of Child Health and Human Development; and highly promising interagency collaborations between NSF and EPA on watersheds and on valuation and decision making. It has proven especially important to find ways to meld a strong social scientific base with substantive focus on global change questions. Useful strategies have included interdisciplinary review of proposals; development of problem-focused initiatives at NSF; incorporation of strong social science input into the peer review process in mission agencies, sometimes drawing on NSF for support; and formal interagency collaborations.

It is also important to encourage international collaborations, to exchange ideas, improve access to data, engage in international comparative research, and take advantage of synergism among research efforts. The IHDP, under the auspices of the International Council of Scientific Unions and the International Social Science Council, has brought the international research community together in two major international conferences[148] and now has active core projects on land use and land cover change, industrial transformation, environmental security, and institutions. The IHDP currently provides a framework for collaboration among social scientists and coordination of national human dimensions programs. The IPCC also provides an important forum for the interchange of ideas concerning the human causes, impacts, and responses to climate change. Recently, regional networks and organizations, such as the Asia Pacific Network, the Inter American Institute, the European Community, and the System for Analysis, Research, and Training (START) are developing human dimensions research programs.

Significance of Improved Observational Methods and Data Systems

Observation, that is, the collection of data, relies on sources ranging from remote sensing platforms on satellites to social surveys. The quality of social data that serve global change research has been improved by applying cognitive laboratory techniques to the way survey questions are asked and using multilevel models and datasets to incorporate community, household, and individual factors into the same analyses. Longitudinal datasets collected by the U.S. government, such as the Residential Energy Consumption Survey, the Nationwide Personal Transportation Survey, the Consumer Expenditure Survey, the National Longitudinal Survey of Youth, the National Survey of Families and Households, and others, have permitted the use of more complex statistical models to understand underlying causal processes. These techniques have been further developed through privately conducted government-funded surveys, such as the Panel Study of Income Dynamics and the General Social Survey. New multicountry survey studies of environmental beliefs, attitudes, and consumer behavior will benefit from these advances.

Systems for linking datasets and increasing their availability provide opportunities for major advances in human dimensions research. The past 10 years have seen the establishment or linkage of several international databases of use in studying the human dimensions of global change. For example, a 1996 report[149] on the global environment provides an accessible compilation of international environmental trends at the country level from disparate sources, including various United Nations agencies and the World Bank. It is becoming the norm in the human dimensions community that data collected with federal funds should be placed in the public domain. The key issue now is implementation. The NASA-supported Social and Economic Data and Applications Center (SEDAC) is charged with making social, economic, and Earth science data available to the entire research and policy community. SEDAC also hosts a World Data Center—A, covering human interactions with the environment, and a data system for

IHDP. Environmental data must be integrated with social datasets already archived by organizations such as the Institute for Cooperative Programs in Survey Research or by researchers who maintain their own distributional mechanisms. Improved access to data via the World Wide Web, along with advances in software and metadata standards, have greatly improved the ability of researchers to search for specific types of data and then manipulate or download them.

RESEARCH IMPERATIVES

Although considerable progress has been made in understanding the human dimensions of global environmental change, there are still many unresolved questions and several important new areas for research. In the committee's review of progress, we identified many areas where knowledge was lacking or research results were inadequate. In this section we attempt to crystallize a research agenda of high-priority questions that might yield valuable information in the next 5 to 10 years, given sufficient attention and resources. These research imperatives have emerged from recent meetings and reports of National Research Council (NRC) committees with an interest in human dimensions research,[150] from a review of other national and international efforts to identify research priorities, and from consideration of the significant intellectual gaps and opportunities identified in the review above.

Some of these research imperatives directly support particular themes of the USGCRP, such as atmospheric chemistry and seasonal to interannual climate prediction (see Table 7.4). Some focus on particular elements of the traditional

TABLE 7.4 Human Dimensions Research Imperatives in Relation to Key USGCRP Science Themes

	USGCRP Science Themes			
Human Dimensions Research Imperative	Atmospheric Chemistry	Dec-Cen Climate Change	Seasonal to Interannual Climate	Ecosystems
1. Consumption	XX	XX		X
2. Technological change	XX	XX	X	X
3. Climate assessment		XX	XX	X
4. Surprises	X	XX	XX	X
5. Institutions	X	XX	X	XX
6. Land use/migration	X	X	X	XX
7. Decisionmaking/ valuation	X	XX	X	X
8. Scientific integration	XX	XX	XX	XX
9. Data links	X	X	X	X

NOTES: XX, strong relevance; X, some relevance.

TABLE 7.5 Human Dimensions Research Imperatives in Relation to Key Human Dimensions Themes

	Key Human Dimensions Themes			
Human Dimensions Research Imperative	Causes	Consequences	Responses	Driving Forces/ Social Process
1. Consumption	XX	X		XX
2. Technological change	XX	X	XX	XX
3. Climate assessment		XX		X
4. Surprises	XX	XX		X
5. Institutions	X	X	XX	X
6. Land use/migration	XX	X		XX
7. Decisionmaking/valuation	X	XX	XX	X
8. Scientific integration	XX	XX	XX	X
9. Data links	X	X	X	XX

NOTES: XX, strong relevance; X, some relevance.

framework of causes, consequences, and responses used in human dimensions research (see Table 7.5). Others cut across several of these themes, develop understanding of fundamental social processes that affect human-environment interactions, or suggest broadening of the overall USGCRP agenda.

Social Determinants of Environmentally Significant Consumption

Previous research has identified changes in the use of land, energy, and materials as priority subjects in understanding the causes of global change. Although the driving forces for the use of these resources include population growth and technological change, in many regions the most important determinant of environmental impacts is the per capita consumption of energy and materials. Debates over the relative roles of "northern" consumption and "southern" population growth, and over the responsibility of different social groups within countries, have confounded international environmental negotiations and domestic policy development. A recent report[151] identifies the study of environmentally significant consumption as an important area for research, a point that is echoed by the recent joint statement on consumption of the National Academy of Sciences and the Royal Society of London, as well as by new research initiatives of the Organization for Economic Cooperation and Development and the European Community.

Consumption, that is, the human transformation of energy and materials, is environmentally significant "to the extent that it makes materials or energy less available for future use, moves a biophysical system toward a different state, or, through its effect on those systems, threatens human health, welfare, or other things people value."[152] Environmentally significant consumption and direct alterations of biological systems are the two main ways in which humanity affects the global environment.

Currently, the most environmentally significant consumption from a global perspective consists of the major activities that burn fossil fuels (e.g., travel, space heating and cooling, electricity production, industrial process heating) and activities that use chlorofluorocarbons, nitrogen, and certain other materials responsible for stratospheric ozone depletion, pollution of ecosystems, and other global environmental changes. Other activities (wood and water use, meat and fish consumption, toxic chemicals and waste disposal) are considered of greater environmental significance at local levels and by some groups. New information about biophysical processes can improve understanding of the relative environmental importance of consumption activities.

Two trends in consumption are of the greatest importance to global change. One is the rapid growth of consumption associated with the emergence of a global middle class—growing segments of populations, particularly in developing countries, that are able to afford the consumptive amenities of the developed world, such as motor vehicles, refrigeration of food and living space, and air travel. The other, potentially countervailing, trend is toward decreased consumption per unit affluence, particularly in wealthy countries, probably brought about by technological improvements, saturation of demand for some amenities, the increasing effectiveness of environmental movements, and shifts in the structure of economies. At the global level, the central question about consumption is whether the second trend can counteract the first before consumption causes unacceptable environmental changes. Below the global level, however, the question looks quite different from the vantage points of high-income and low-income countries and populations, which differ greatly in how much benefit they perceive from further increases in consumption.

The social determinants of environmentally significant consumption[153] include changes in human populations, development and diffusion of consumptive technologies and behavior patterns, economic resources available to households and firms, prices of fuels and equipment, human values and preferences, availability and use of information, structural change in economies, and public policies. One of the overall challenges is to understand the links between individual demand for goods and services and the ultimate environmental impacts of meeting those demands. Particular human needs and wants may be satisfied by a variety of products and processes that cause different types and magnitudes of environmental change. Understanding the connections can help in finding ways to decrease the environmental impact of meeting human needs.

Over the next decade, research on environmentally significant consumption should address major questions such as the following:

- What are the constituents and determinants of energy use and other environmentally significant consumption in countries and populations at different levels of economic development?
- How is consumption likely to change with increasing affluence in low-income countries and populations and does this change always follow the path that high-income countries and populations have followed?
- What social forces drive the most environmentally significant consumption types, such as travel, the diffusion of electrical appliances, agricultural intensification, water use, and purchases of high-energy-consuming vehicles?
- What are the relative roles of various determinants of consumption in different countries?
- What policies at the national level lead to greater attention in communities to such issues as urban sprawl, reducing the cost of home-to-work commuting, expansion of green spaces, and enhanced recycling of materials?
- Which materials transformations have the greatest environmental significance and what determines related kinds of consumption?
- What interventions can effectively alter the course of the most environmentally significant kinds of consumption?
- What determines public support for effective consumption policies and how do these factors vary across countries?

This research will involve analysis of disaggregate data on particular consumption types in relation to prices, policies, and physical infrastructure within countries; surveys of consumption behavior and related values and beliefs in households and firms; data comparisons across consumption types and countries; and experiments with interventions. It will also attempt to understand how culture, fashion, advertising, and various kinds of opportunities and constraints influence consumption and will investigate the ways in which economic and cultural globalization and corporate and government decisions increase, limit, or expand individual consumer choices.

Over the next 5 to 10 years this research can meet several critical goals:

- Improve understanding of the constituents, determinants, and time paths of energy use in developing countries, thus improving the ability to model and anticipate anthropogenic carbon emissions, use of biomass fuels, and emissions of local and regional air pollutants.
- Improve projections of emissions and pollution in high-income countries, along with understanding of the key behaviors driving those emissions.
- Improve understanding of how changes in water, food, and wood consumption influence land use and vulnerability to climate variability and change.

- Promote more realistic analyses of the policy options for achieving national and international targets (e.g., limitation of greenhouse gas emissions, control of regional air quality, more efficient use of water resources), taking into account knowledge about public acceptability and the requirements of successful implementation.

This research priority will develop basic understanding of consumption and provide insight about its causes, dynamics, and trajectories that will be essential for making informed decisions. It will also provide important support for scientific research in atmospheric chemistry and decadal to centennial climate change, in understanding how water demands create vulnerability to climate change and variation and how ecosystem pollution and food and materials consumption are drivers of land use change.

Sources and Processes of Technological Change

The rate of technological change is one of the most significant sources of uncertainty in climate models as well as in understanding future uses of land, ecosystems, and water. Moreover, development and adoption of new technologies together constitute one of the most important methods available for achieving national and international commitments to environmental protection and sustainability.

Improving emissions scenarios for greenhouse gases and other globally significant pollutants such as SO_2 and hydrogenated chlorofluorocarbons requires not only more accurate demographic trajectories but also sectoral studies of changes in consumption and technology, particularly in developing countries. The implementation and enforcement of international treaties to control ozone depletion and greenhouse gas emissions and the projection of future changes in atmospheric chemistry all will require a much more realistic and geographically disaggregated assessment of land use, technology substitution, consumer preferences, incentives, and trade than has been undertaken to date. This effort requires research ranging from studies of the industrial ecology of individual sectors, firms, and farms to analyses of corporate strategy, trading relations, and responses to regulations.

Over the next decade, research on technological change and the environment should address such questions as these:

- What factors determine variations among sectors and actors and change over time in the approximately 1 percent per year decrease in national energy intensity generally attributed to technological change?
- What factors determine average rates and variations around the average in the adoption of new production technologies that reduce inputs of energy and virgin materials per unit output?

- What factors determine the rate at which production costs of an environmentally benign technology decline as output increases?
- What have been the effects of prescriptive standards, best-available-technology rules, public recognition, and awards to encourage voluntary technology adoption and other technology-related environmental policy instruments on actual rates of innovation?

This research on technological change will involve econometric modeling of change in energy and materials productivity and case studies of technology adoption in firms and industries, changes in production processes, and responses to regulation and incentives, and case comparisons. Over the next 5 to 10 years this research can achieve the following:

- Account for a significant proportion of variance in "autonomous" energy efficiency improvements, thus enabling more accurate modeling of improvements in energy intensity and identifying factors responsible for rapid efficiency improvements in some sectors and by certain actors.
- Identify characteristics of technology-related policy instruments associated with more rapid innovation by industries.
- Identify important sources of variation in technology adoption across firms within industries.
- Identify some of the causes of "learning" in production processes.

Research on technological change, particularly research documenting rapid adoption of environmentally beneficial technology, will suggest effective policy options for encouraging beneficial technological change. It is also critical to improving the modeling and anticipation of the climatic impacts of greenhouse gases, to understanding regional changes in atmospheric chemistry, and to examining the role of technology in human impacts on terrestrial and marine ecosystems.

Regionally Relevant Climate Change Assessments and Seasonal to Interannual Climate Predictions

One of the great challenges of global change research is to make scientific information, such as the results of climate modeling and analysis and studies of vulnerability and adaptation posibilities, more relevant to decision making at the local level. Regional assessments have been identified as a priority by the IPCC, the USGCRP, and the International Research Institute for Climate Prediction. Regional assessments can be developed for scenarios of global warming, decadal climate shifts, and seasonal forecasts and have the potential to address many issues of concern to local resource managers, corporations, and citizens. This research priority is also highly relevant to scientific efforts to provide more useful seasonal to interannual climate predictions and to understand decadal to centennial shifts and changes in climate.

An important intellectual shift in climate impact assessment in recent years has been an increased focus on understanding vulnerability and adaptation. Understanding how global warming or ENSO will affect a local region is as much a question of understanding the social and economic characteristics of the region as it is of obtaining the appropriate results from a climate model. For example, drought impacts on crop production are mediated by access to adaptive technologies such as irrigation, fertilizer, and seeds, as well as crop prices and subsidies and coping mechanisms such as environmental information and insurance. Adaptive technologies and coping mechanisms vary considerably by region, sector, and social group. Thus, improved regional assessments require detailed studies of how vulnerability develops and can be reduced. Future models and economic analyses are likely to include vulnerability indicators and findings about processes that affect vulnerability.

Research priorities for understanding the impacts of long-term climate change should address some of the agendas established by the IPCC. These would include studies that take advantage of mesoscale model outputs and downscaling techniques to improve regional projections of climate impacts and detailed analysis and longer-term projections of changing vulnerability and adaptive strategies. As scientific understanding of other decadal shifts in atmospheric and ocean circulation improves, the research might also focus on climate interactions with the management of resources such as ocean fisheries, forests, and water and agricultural systems. For example, the dynamics of fisheries in the context of decadal climate shifts cannot be understood without an understanding of human pressures on marine resources.

In the area of seasonal to interannual climate prediction, an NRC panel has developed a research agenda to increase the social usefulness of such predictions.[154] As described in Chapter 5, there have been significant improvements in our ability to forecast climate 3 to 12 months in advance, especially in relation to changes in sea surface temperature and atmospheric circulation associated with ENSO. Because ENSO appears to be correlated with large impacts on agriculture, health, water resources, and ecosystems, this improved forecast capability has significant implications for people, especially when combined with information on vulnerability and adaptive responses.

The NRC panel considered such issues as measuring and monitoring the social impacts of climate variability, analyzing changes in vulnerability to climatic extremes and variations in vulnerability across social groups, and identifying opportunities and barriers for the beneficial use of seasonal forecasts, including improved understanding of interactions with markets and improved communication of uncertainties in the policy process and to forecast users. Research to make climate predictions more socially useful must be undertaken with close links to researchers and policy makers in affected regions and with frequent communication with those producing the predictions. As understanding and predictability extend to new regions, lead times, and levels of certainty, human dimensions research can provide important insights into local vulnerability and policy contexts as well as into human needs and responses to improved climate information.

Over the next decade, research to make climate predictions more useful at a regional level should focus on a number of questions, including the following:

- What are the sectoral impacts at the regional level of climate change and seasonal to interannual variations?
- Are there impact and vulnerability indicators that can be useful to detect the extent and severity of the impacts of global change on human populations?
- Can historical data be used to project future human vulnerabilities to climatic variation and change?
- How does climate change interact with other social and ecological changes to influence crop yields, water use, and other impacts?
- Can the mesoscale outputs of climate models be better linked to models predicting the regional impacts of climate change?
- How are the impacts of climate change and variability affected by the coping techniques available to vulnerable groups?
- When science can provide early warnings of possible catastrophes, how can this information be transformed effectively into public understanding and appropriate policy responses?

This research will include case studies of responses to past climate variations; quantitative analyses of the social and economic consequences of such variations, including adaptations and the distribution of impacts across regions and social groups; development and testing of vulnerability indicators against past data; building of models that project future vulnerability; development and linking of models; and analysis of responses to climate forecast information.

Over the next 5 to 10 years this research should be able to develop the following:

- Methods for linking mesoscale and other climate model outputs to models of regional water resources, agricultural production, energy needs, and health conditions.
- Assessments of the vulnerability of many regions to climate change and variation.
- Estimates of the potential regional impacts of future climate change and variability and the value of improved climate information, including seasonal forecasts.
- Improved methods for delivering climate forecast information.

Social and Environmental Surprises

Natural science research has identified and is evaluating several kinds of rapid and discontinuous environmental changes that might overwhelm human adaptive capacities, at least in some localities. They include rapid climate change events (as from a major disturbance of the North Atlantic Oscillation), major outbreaks of diseases in humans or key crop species, and rapid destruction of the reproductive capacity of key ecosystems resulting from chemical releases to the environment. The damage to society should such changes come to pass is obvious; it is less obvious how to deal best with the prospects of such changes. Societies must function and plan for the future in the face of continuing revelations from environmental science and high uncertainty about potential catastrophes. We must also deal with meta-uncertainty—not knowing how uncertain we are.

It is not just rapid environmental changes that may produce global change surprises. Social systems can also change rapidly and discontinuously in ways that may greatly alter environmental systems and human vulnerability to global change.[155] History provides a number of illustrations of such changes, including the environmental impact of European political decisions to colonize (including the rapid spread of diseases and land use changes) and the impact of regional and global warfare on resource consumption and ecosystems. More recent rapid political and economic changes also have major global change implications. For example, the collapse of the Soviet political bloc altered greenhouse gas emissions and land use, restructured trade and property rights, and altered political alliances. The environmental and social implications of such rapid change should be a research priority. Another form of dramatic social change has been the rapid spread of democratization and liberal economic policies in Latin America and Africa. These too alter human-environment relationships in unforeseen ways. As economic liberalization changes the terms of trade, land use and industrial production can change quickly, with pollution patterns shifting along with industrial relocation and deregulation and vulnerability to climatic extremes changing with the restructuring of agriculture and food systems. Democratization can transform public attitudes and open up decision-making processes to popular movements, altering the policy process responsive to global change. One of the most challenging questions is to understand how these rapid social changes may interact with rapid environmental change.

Some of the key questions about surprises for the next decade are the following:

- What are the human consequences of rapid climate changes in the past and present?
- What are the global environmental change implications of rapid political and social changes in the past and present?

- How have environmental and social surprises interacted?
- Which human activities (e.g., patterns of land use and management, chemical releases) can significantly alter the potential for major environmental surprises?
- When science can provide early warnings of possible catastrophes, how can this information be transformed effectively into public understanding and appropriate policy responses?
- How can hazard management systems, including insurance strategies, subsidies, technological investment, and warning systems, be organized to increase resilience in the face of major surprises and at what cost?
- How can society deal with the possibility that citizens will become immobilized by warnings of possible, but highly improbable, environmental catastrophes?

Research on environmental surprises should include comparative studies of past environmental catastrophes and hazard management systems, simulations that superimpose plausible hazard events on existing hazard management systems, and experiments to test responses of individuals and organizations to information about possible environmental surprises.

Research in the next 5 to 10 years can achieve the following:

- Document and analyze the environmental implications of recent rapid social changes, such as post-Soviet restructuring, democratization, trade liberalization, and resource privatization.
- In collaborations between social scientists and natural scientists, significantly elaborate the human dimensions of credible but low-probability geophysical catastrophes, ecological collapses, and disease outbreaks.
- Examine the consequences of and responses to catastrophes in the historical and prehistoric records, to identify the characteristics of hazard management systems that have been associated with effective response in the past.
- Evaluate the immobilization hypothesis and, if it is a serious threat to response, suggest ways of presenting information about possible surprises that could overcome such tendencies.
- Develop some practical approaches through which those responsible for hazard management systems can consider the implications of catastrophe scenarios for those systems.

Effective Institutions for Managing Global Environmental Change

To make effective and well-informed decisions to anticipate the threat of global environmental change, society needs better understanding of how social institutions influence environmentally significant human actions. This need can be seen from the following observations: international agreements set targets without much consideration to what is feasible; governments often set resource extraction limits at unsustainable levels; national policies often appear to local resource managers to be part of the problem; techniques for estimating the full social costs of natural resource consumption rarely result in either social consensus or policy decisions; institutional change often has unforeseen or unfair distributional impacts; and even when there is widespread agreement about a global change phenomenon among specialists, many people perceive a high level of scientific disagreement. Such difficulties afflict resource management institutions at levels from local to international.

Global and national institutions, which are at the same scale as the problems, must be better coordinated with local institutions, which are often at the same scale as the solutions. Decision makers need more information about how to achieve this coordination. They also need to develop institutional approaches for allocating environmental resources when market prices give incomplete or misleading information. Research on environmental management institutions advances our understanding of the causes, consequences, and responses to global change and should thus be given a high priority.

Over the next decade, research to meet these needs should address such questions as the following:

- What are the characteristics of effective institutions for managing global environmental change?
- What are the correlates of effectiveness for the management of international environmental and natural resources by international regimes and institutions? In particular, what are the conditions favoring effective implementation of commitments to protect biodiversity, forests, oceans, and stratospheric ozone and to prevent climate change?
- What are the implications, applicability, and limits of particular policy instruments, including market-based instruments and alterations in property rights institutions at international, national, and local levels?
- How do declaratory targets, consensus policies, and review processes interact to influence behavior and restructure the power relationships of states and nonstate actors?
- Which characteristics of national institutions are most conducive to sustainable resource management by local institutions?
- How can knowledge about the conditions for successful local resource management be applied to problems at national and international levels?

Research on these questions will demand a variety of methods, including systematic empirical study of existing regimes and institutions for managing global change issues at levels from the international to the local; conceptual studies of proposed institutional policy instruments, focusing on bargaining problems and links among international, national, and local levels; theoretical studies of the bargaining, contracting, and principal-agent aspects of implementing commitments at higher levels by delegating substantial authority to lower-level agents (e.g., tradable permit systems, joint implementation, federal systems); institutional and political study of the applicability of institutions at lower levels of organization to the design of national and international policy instruments; quasi-experimental studies, case comparisons, and simulation studies of the effects of major changes in institutions and rules, based in part on data from archival records and the recollections of participants; and small-scale simulations and experiments.

Over the next 5 to 10 years, research on these issues can be expected to lead to a number of achievements:

- Identification of conditions, potential contributions, and pitfalls associated with specific policy instruments, such as tradable permits, and with specific designs of environmental institutions.
- Development of a larger and more consistent body of data on international institutions and regimes and on regional and local property rights and other institutions with which to conduct comparative studies of their formation, evolution, and influence.
- Identification of conditions under which particular national policies assist or impede the efforts of local resource management institutions to sustain their resources and identification of insights from the experience of local resource management institutions that are transferable or adaptable to national and international institutions.
- Identification of the contributions of process-based international review mechanisms to changed behavior.

Changes in Land Use/Land Cover and Patterns of Migration

Considerable progress is already being made in understanding land use/land cover change and changes in human population processes. All land use is local, but the forces influencing the dynamics of land use and land cover come not only from individuals, households, and communities but also from processes at regional, national, and global levels. To understand land use and land cover change requires knowledge of how forces within and beyond the individual actor combine to affect decisions, particularly the conditions conducive to land use decisions that are either destructive or restorative to the environment. We do not yet fully understand how individual perceptions, attitudes, and socioeconomic situations affect land use choices or precisely how various external conditions, such as trade and international political economy, in addition to local rules for access to resources, insurance regulations, distance to markets, infrastructure development, and other factors, interact in the calculus that people use in making decisions about resource use.

One of the current challenges in understanding land use change, as well as changes in the use of water, marine ecosystems, and other resources, is characterizing the role of population in environmental change and degradation. As noted, considerable progress has been made in understanding population-environment relationships and in explaining more basic population dynamics. There is some agreement that, in the future, migration, rather than changes in human fertility and mortality, will be the key demographic link between the two dynamic processes of land use and land cover change. Causation and feedback will probably move in both directions: environmental changes will likely cause migration, and migration will likely change the environment. Careful research into the relationships between population mobility and environmental change is also needed because of the growing popular concern with environmental refugees, the environmental impacts of immigration, and the role of population in environmental conflict and security.[156] There is very little empirical documentation of the relationships between migration and environment.

Population migrations in the United States, however, illustrate the process. There were large migrations into the Midwest from the middle of the nineteenth century until about 1920, after which time the population of the country became increasingly urban—until the past decade, that is, when, across the country, a growing number of households have moved outside of cities and either commute to work or work at home part of the time. This shift, if it continues, may have significant environmental consequences in terms of the consumption of fossil fuel and other resources and for land use and land cover.

To understand the interaction of migration patterns and land use/land cover change requires improved data and data analysis both on prior migrations and intended future migrations. Data are needed for individual and household levels, as well as for more aggregated levels. Data on migration and other social variables must be linked with biophysical data from remote and land-based sources on soils, climate, and other biophysical factors. The data must be collected and coded in such a manner that they can be geo-linked at spatial and temporal scales with resolutions appropriate for the theoretical issues addressed. The necessary temporal depth can be achieved through prospective and retrospective techniques. Retrospective approaches allow temporal depth in a cross-sectional survey; prospective approaches permit the inclusion of intentions and attitudes, which cannot be obtained retrospectively. The social science community is now in a position to collect and analyze the requisite migration data. In the past 15 years, considerable progress has been made in improving the quality of retrospective migration data by embedding its collection in a broader life history approach. More recently, advances have been made in collecting prospective migration data by incorporating the insights of social network analyses into the data collection process. Methodological aspects of geo-links to biophysical data are currently being worked out.

The potential now exists to significantly improve understanding of the interrelationships between human spatial movements and land use/land cover change. Assuming that sufficient migration data are collected to cover both points of origin and receiving areas, we can move beyond such simple statements as "large migrations of individuals and families into a given area affect the land use/land cover patterns in that area." Such research accomplishments will involve disaggregating both migration streams and land use/land cover change patterns so that specific attributes of migrants can be related to specific aspects of land cover and land use. For example, does the migration of young adults or the elderly have a larger impact on patterns of forest regrowth in rural areas or on water use?

Research priorities for land use studies have been established internationally through the IHDP/IGBP core project on land use/land cover change.[157] The U.S. research community should maintain collaborative ties with IHDP/IGBP, and the USGCRP should work to ensure that this collaboration is maintained. Research over the next decade should address such questions as the following:

- What are the links among land use change, migration, political and economic changes, cultural factors, and household decision making?
- What are the interrelations between migration and environmental change?
- What comparative case studies of land use and land cover change are useful for understanding and modeling land use change at regional and global scales?

This research will include efforts to map land use and land cover and will document changes over time, develop and validate classifications of land use and land cover, develop algorithms for making the classifications accurately from remotely sensed data, undertake comparative and statistical analyses of past relationships between changes in social driving forces and land use and between land use and land cover, and develop and test regional and global models of land use and land cover change. Research progress will depend on remotely sensed data, which can provide key information on land cover and are needed at appropriate spatial and temporal resolutions.

To obtain data on past population migrations and other social driving forces, continued and improved access to earlier generations of remotely sensed data is imperative. Data collected for military and/or intelligence purposes need to be increasingly declassified and made available to the research community. This need applies to data sources of both the United States and the former Soviet Union. For future remote sensing instruments, fine-grain spatial resolution is critical, as is the ability to determine the height of buildings in urban areas. This research should take advantage of the development of enhanced, multilevel, multiscale, and comparative methods in the study of human communities across the planet;[158] it can also make use of Earth-observing satellites that offer 1- to 3-m resolution and that facilitate observation, archiving, and analysis of human impacts at that scale. Success will depend on collaboration between social scientists and physical scientists in developing better algorithms for analyzing the large datasets provided by fine-resolution satellites to address behavioral questions.[159] Use of remotely sensed data at this fine scale will require attention to confidentiality in archiving and can benefit from past experience with social data.[160]

Over the next 5 to 10 years research on land use issues can be expected to meet a number of goals:

- Development of datasets and comparative empirical studies on the social causes and consequences of land use and land cover change in different regions that will permit improved understanding of the relative roles of population dynamics, economics, and other factors in driving environmental change.
- An improved capability to include detailed land use and land cover information in regional- and global-scale models and the development of prototype land use models that can be validated and used to identify gaps in knowledge.
- Use of a wider range of satellite data to study human-environment interactions.
- Improved understanding of the relationship of population mobility to land use change, including the dynamics and environmental impacts of migration.

Methods for Improving Decision Making About Global Change

The link from science to policy is a major weakness in human response to global change. Although science-based understanding is essential for making informed decisions, it is not always obvious to scientists which information would be considered useful and relevant by participants in environmental decisions. It is also difficult for international, national, and local decision makers to make sense of available scientific information on complex environmental systems, much of which is uncertain or disputed and all of which is subject to change. Well-informed choices are even harder to make because they must be acceptable to decision participants who do not share common understandings, interests, concerns, or values. Research should pursue three related aims: improving methods for valuing nonmarket goods; improving analytical methods for integrating multiple types of decision-relevant information (e.g., integrated assessment models, cost-benefit analyses); and developing decision processes that effectively combine analytical, deliberative, and participatory approaches to understanding environmental choices and thus guide scientists toward generating decision-relevant information.

Over the next decade this research field should address a number of questions:

- Are there ways to improve economic assessments of the costs, benefits, and distributional effects of forecasted climate changes and variations, taking adaptive capacity into account?
- What are the best ways of communicating uncertainty, providing early warnings of food and health problems, and introducing climate information in the policy process?
- How can environmental quality be incorporated into national accounting systems, so that it can more easily be considered in the policy-making process?
- How can information about the nonmarket values of environmental resources be incorporated effectively into decision making about resource use?
- How can we better represent, propagate, analyze, and describe uncertainties and surprises in integrated assessment (e.g., integrating quantitatively specified uncertainty with subjective probability distributions, clarifying the relationship between uncertainty and disagreement)?
- What are the characteristics of institutional processes that ensure that scientific analyses are organized so as to meet the needs of the full range of decision-making participants for information and involvement?
- How can the knowledge and concerns of those participating in or affected by environmental decisions be used to inform scientists about how to make environmental information more decision relevant?
- How do expert advice and assessment influence policy, decision making, and collective knowledge of global change issues and how do policy makers interpret information about scientific uncertainty as they frame global change issues?
- How can decision-making procedures be structured to bring the quantitative and formal information embedded in assessment models together with scientific judgment and the judgments, values, preferences, and beliefs of elite and nonelite citizens in decision-making processes that meet the informational needs of the participants and are appropriate to the decision at hand?

Research to improve analytical techniques will use such methods as model development, with particular attention to the modeling and propagation of uncertainties through complex systems, dialogue among modelers using different methods for analyzing the same issues, experimental studies of methods for quantifying the nonmonetary values of environmental resources, and surveys to identify those values. Research to improve decision-making processes will use case studies and comparisons of existing systems that inform management decisions and will conduct experiments and simulations to test alternative processes, particularly methods that involve broadly based deliberative processes, for informing scientists about decision participants' information needs and for informing policy debates.

Over the next 5 to 10 years research on these issues can be expected to yield the following:

- Improved methods for describing uncertainty, scientific disagreement, and the potential for surprise in environmental systems (e.g., subjective probability distributions based on expert elicitation, discursive methods).
- A theoretically grounded understanding of the sources of apparent anomalies in expressed-preference methods of estimating nonmarket values of environmental goods and services.
- Clarification of the nature of conflicts over cost-benefit analyses and other techniques of integrating information in support of environmental policy decisions.
- Improved understanding of the conditions under which particular analytical approaches meet the needs of decision-making participants for information and involvement and the conditions under which these approaches need to be supplemented with other techniques.
- Improved ability to incorporate scientific information within deliberative processes that involve scientists, policy makers, and interested and affected parties in informing and making environmental policy decisions. An experimental effort should be undertaken to use dialogue among scientists, policy decision makers, and interested publics to identify promising research areas that would lead to information directly usable for policy. The current national assessment effort might be studied as an experiment in this sort of dialogue and used to identify some new and important research directions.

Improve Integration of Human Dimensions Research with USGCRP Science Themes and with Other International Research

As outlined in the USGCRP's (1997) *Our Changing Planet*, human dimensions research should be a component of each science theme as well as a cross-cutting issue. What is needed now is to organize the USGCRP so as to make this a reality. For each of the program's four major research themes, key human dimensions research activities relevant to that theme must be identified and supported. For example, atmospheric chemistry would include research on the consumption patterns and technologies that drive emissions-altering atmospheric chemistry, on the impacts of UV changes, and on the institutions and decision-making processes that result in the control of these emissions (e.g., the Montreal Protocol and its implementation). The theme area of seasonal to interannual climate prediction would include support for research on vulnerability to climate variations and the social implications of seasonal predictions. Decadal to centennial climate change research would incorporate research on consumption and land use changes that alter the global carbon cycle; the driving forces behind these changes; the vulnerability of water resources, agriculture, and fisheries to decadal shifts in ocean-atmosphere circulation; and the social and environmental effects of policies to limit greenhouse gas emissions. Terrestrial and marine ecosystem studies would encompass work on human causes, consequences, and responses to ecosystem changes, including an increased emphasis on ways in which institutions (in the broadest sense of property rights, laws, and markets) promote and prevent land use and ecosystem changes; integrative assessments of the interactions between natural variations and human exploitation of fisheries, grasslands, and forests; and studies of the human impacts of ecosystem changes resulting from multiple stresses (e.g., ecosystem changes and climatic changes). Some steps are currently being taken toward such integration (e.g., NOAA's effort to develop a research agenda on the human dimensions of seasonal to interannual climate prediction). Such efforts need to be encouraged and their research recommendations implemented.

Structuring support for human dimensions research only around themes defined by natural science is inadequate because certain human dimensions issues cut across all of the research themes and require crosscutting and independent research initiatives. These initiatives include those on valuing environmental quality, the problem of developing improved methods for environmental decision making, and some questions about the human driving forces of environmental change. The challenge of organizing research on these crosscutting topics is confounded by multiagency responsibilities for funding. The research priorities identified in this chapter cannot be addressed without focused and coordinated funding. NSF, the agency responsible for the largest share of designated human dimensions research funding within the USGCRP, is the agency with the most experience in engaging basic social, behavioral, and economic science expertise and in providing a strong peer review system for proposals. However, NSF funds primarily investigator-initiated and disciplinary, rather than problem-oriented and interdisciplinary, social science research. Many of the other agencies currently have very small budgets ($1 million to $3 million) devoted to human dimensions research, which restricts them to supporting research focused on the particular agency's responsibilities. The danger exists that certain critical research areas will be perceived as too crosscutting for funding by mission agencies and too interdisciplinary for funding by NSF.

Basic social science research on human dimensions administered by disciplinary programs at NSF in response to investigator-initiated proposals is very important. But support is also needed in the form of interdisciplinary review panels, interagency collaborations, and research driven by specific science plans and organized in centers of excellence to advance human dimensions research. There are good models provided by the now-defunct human dimensions review panel at NSF, the recent Human Dimensions Centers and Methods and Models in Integrated Assessment initiatives, and the joint NSF-EPA partnerships in environmental research. The last collaboration supports research on decision making and valuation in environmental policy and on water and watersheds. Similar partnerships could address the research priorities identified in this document on environmentally significant consumption (NSF, EPA, and DOE), land use change (NSF, NASA, DOI), and regional climate assessment (NSF, NOAA, NASA).

Recent developments in international human dimensions infrastructure and planning make it increasingly important for the USGCRP to support U.S. participation in new international research projects and networks. This participation will allow the USGCRP to leverage funds and research contributions from other countries and to strengthen scientific capability in the United States and in developing countries. The USGCRP should support both core activities and U.S. participation in those IHDP programs that are well planned and truly international, as well as other regional and international networks such as the Inter American Institute, Asia Pacific Network, START, and the International Research Institute for Climate Prediction as they organize high-quality human dimensions research. We are at a critical juncture in the development of many of these international programs and networks, and there are opportunities to participate in new and important research collaborations and to assist in defining international research agendas that should not be missed. Many countries are about to organize new human dimensions research initiatives and establish national advisory committees. There are important opportunities for regional and bilateral collaboration with institutions such as the European Commission (1995) through NAFTA, and with Japan and other countries making a renewed commitment to human dimensions research.

Improve Geographic Links to Existing Social and Health Data

With few notable exceptions, social science data have been collected without concern for research questions about the human dimensions of global environmental change. The data collection efforts have mainly been driven by other needs and paid for by agencies that are not part of the USGCRP. As a result, the overwhelming majority of the publicly available social science datasets, although potentially relevant to global change research, are not as well suited as they might be to this purpose. Several steps could be taken to improve this situation. First, when links from social science data to other observational sources are necessary, the USGCRP could make a marginal investment in the ongoing data collection to ensure that sufficient geographical location information is collected to permit linking with data from relevant observational platforms.

Assuming the requisite geographical linkage data are obtained, the issue of protecting the confidentiality of respondents arises. Below the country or perhaps provincial scale, virtually all social science data are obtained with the promise of protecting the confidentiality of individuals, households, organizations, and often communities. For a variety of ethical reasons it is essential that this confidentiality be maintained. Yet doing so makes it impossible to have geolinked public use files for the research community. Efforts need to be made to facilitate building a secure system that can link social science data to biophysical data to meet legitimate research needs while simultaneously protecting the confidentiality of respondents.

Solutions might include the establishment of physical places where researchers could go to do their analyses under appropriately supervised conditions or a system that involved appropriate legal safeguards backed up by enforceable penalties. The involved federal agencies need to establish a mechanism to study the problem and put an effective solution in place. Without effective solutions, scientific progress will be severely constrained.

Linkages between human health and ecosystem information can combine environmental monitoring with consequences and impact monitoring. For example, NSF's long-term ecological research site in New Mexico now traps rodents for hantaviruses, in collaboration with the Centers for Disease Control and Prevention. Data systems that integrate health outcomes with remote sensing/ geographic information system mapping can help researchers evaluate climate and land use impacts on food sources, predators, and habitats for rodents and other ecosystem changes with human consequences.

Linking social and biophysical data presumes stable funding for archiving and disseminating human dimensions data and sufficient financial resources to permit upgrading as the storage and dissemination technology changes. Both the Social and Economic Data and Applications Center and the Institute for Cooperative Programs in Survey Research have experienced substantial uncertainties and interannual fluctuations in their funding, which in turn has created problems for the research community. When the dissemination mechanism involves individual projects, mechanisms need to be in place to continue the archiving and dissemination of these datasets after the project is complete.

In addition, the time is right to carefully examine the extent to which existing and planned social science data serve the science needs of the global research agenda. This issue is discussed more extensively in Chapter 9, but brief reference is needed here. The bulk of social, economic, and health data used in human dimensions of global research is collected for other purposes, at scales well below the global level. To date, the principal federal agencies involved in collecting social science data in the United States and abroad (Census Bureau, Department of Labor, Department of Health and Human Services, and Agency for International Development) have not been part of the USGCRP. Furthermore, as discussed earlier in this chapter, human observations raise confidentiality issues that may not be present in other global change research areas. We recommend a careful review of the observational needs for human dimensions research, with careful attention to the ability to link to other observational systems, comparability across time and observational units, and confidentiality concerns.

CONCLUSION: KEY RESEARCH ISSUES FOR THE USGCRP

The USGCRP should address the human causes and consequences of global change and human responses to anticipated or experienced global change. Among the key research issues for the USGCRP should be the following:

1. Understanding the driving forces of environmentally significant consumption. The USGCRP should develop understanding of the ways in which various political, social, economic, and technological forces combine to result in major transformations of land, water, energy, and environmentally important materials. Such understanding will help to both anticipate future environmental changes and identify potentially useful interventions for mitigating environmental changes or easing adaptation to them.

2. Understanding sensitivity and vulnerability to environmental variations and changes. The human consequences of environmental change depend as much on the sensitivity and vulnerability of social systems and on their ability to adapt as on the environmental changes they experience. Thus, the USGCRP should develop understanding of both aspects of consequences. It should improve predictive models of specific environmental changes and variations that have human impacts and develop understanding of the causes and likely future trends of vulnerability and adaptive capacity. This research should include a focus on the characteristics of social systems that make them sensitive or vulnerable to particular environmental changes and on social changes that are likely to alter the sensitivities of particular human populations over time.

3. Understanding institutions and processes for informing environmental choices and managing environmental resources. People must respond to environmental change at all levels of social organization from the individual to the international. Decisions at all of these levels need to be informed by knowledge of biophysical and social processes and by understanding of human concerns. To enable more effective responses, the USGCRP should develop understanding of the characteristics of effective ways to integrate science and human concerns in informing decisions and of effective institutional forms by which human groups at all levels can monitor and manage the use of critical environmental resources. Experimental efforts should be undertaken to use dialogue among scientists, policy decision makers, and interested publics to guide scientists in developing information that will be considered useful and relevant by participants in environmental decisions.

NOTES

1. U.S. Department of Energy (1997), World Resources Institute (1996).
2. World Resources Institute (1996), Food and Agriculture Organization (1997).
3. World Resources Institute (1996).
4. World Resources Institute (1996), U.S. Department of Energy (1997).
5. Kates et al. (1985), National Research Council (1988).
6. Social Learning Group (1998).
7. Scott (1996), Bijlsma (1996).
8. Reilly (1996).
9. Intergovernmental Panel on Climate Change (1996b).
10. Ibid.
11. Caulfield (1985).
12. Moran (1981).
13. Hecht and Cockburn (1989).
14. Skole et al. (1994).
15. Pielke and Landsea (1998), Pielke and Pielke (1997), Greenpeace International (1994).
16. Blaikie (1994).
17. McMichael (1996).
18. Beamish (1995), Hutchings (1996), Brander (1996), Finlayson and McCay (1998).
19. National Research Council (1996a), National Research Council (1999).
20. Thomas (1954), Sauer (1963), Steward (1955), Glacken (1967), Turner et al. (1990), National Research Council (1993).
21. Turner et al. (1994, 1995), Moran et al. (1994, 1996).
22. Deforestation, Skole et al. (1994), Dale (1994); land use change, Rudel (1989), Entwistle et al. (1998).
23. Turner et al. (1995), Moran et al. (1994), National Research Council (1998).
24. Turner et al. (1995).
25. Riebsame (1990), Ojima et al. (1993), Parton et al. (1994).
26. Crosby (1972), McNeill (1992), Richardson (1992).
27. Balee (1994).
28. Tropical deforestation, Allen and Barnes (1985); living standard, Skole et al. (1994).
29. Hayami and Ruttan (1985), Boserup (1981).
30. Hardin (1968).
31. Netting (1981), Ostrom (1990).
32. Blaikie and Brookfield (1987).
33. Tucker and Richards (1983), Hecht and Cockburn (1989), Worster (1988).
34. Moran et al. (1994), Mausel et al. (1993), Brondizio et al. (1996).
35. Guyer and Lambin (1993), National Research Council (1998).
36. Turner et al. (1995).
37. Moran (1995), Skole et al. (1994).
38. Foresta (1992), Gillis and Repetto (1988).
39. Everett (1996).
40. Steele (1996), National Research Council (1996c).
41. Smith (1986), Sinclair (1987).
42. Folke and Kautsky (1996), Bailey et al. (1996), Meltzoff and LiPuma (1986).
43. Stonich et al. (1997).
44. McCay and Acheson (1987), Cordell (1989), Ostrom (1990).
45. Environmental impacts, Schipper et al. (1992), Schipper and Martinot (1993); other factors, National Research Council (1992), Dietz and Rosa (1997).
46. Schipper et al. (1992), Socolow et al. (1994), International Energy Agency (1997).

47. Shafik (1994), Grossman and Krueger (1995), Holtz-Eakin and Selden (1995), Dietz and Rosa (1997).
48. Schurr (1984), National Research Council (1992).
49. International Energy Agency (1997).
50. Wernick and Ausubel (1995), Nakicenovic (1996), Wernick (1996).
51. Energy use, Bohi (1981), Cropper and Oates (1992), Dillman et al. (1983), National Research Council (1984b); social group membership, Lutzenhiser (1993, 1997); individual habits, National Research Council (1984a), Lutzenhiser (1993), Gardner and Stern (1996).
52. National Research Council (1984a), Stern (1992), Gardner and Stern (1996).
53. Incentives, Bohi (1981), Cropper and Oates (1992), National Research Council (1984b), Stern et al. (1986); behavioral and informational factors, National Research Council (1984a), Stern (1992), Gardner and Stern (1996).
54. National Academy of Engineering (1989), Socolow et al. (1994).
55. Wernick and Ausubel (1995), National Research Council (1997).
56. Kinzig and Socolow (1994), Schlesinger (1997).
57. Consumption concept, National Research Council (1997), analysis of materials, National Academy of Engineering (1994), Wernick and Ausubel (1995), *Daedalus* (1996).
58. Schipper and Myers (1993).
59. Nordhaus and Yohe (1983).
60. Lave and Dowlatabadi (1993), Morgan and Dowlatabadi (1996).
61. Intergovernmental Panel on Climate Change (1996a).
62. Rosenzweig (1985), Parry et al. (1988).
63. Rosenzweig and Parry (1994), Easterling et al. (1993).
64. Reilly (1996), Rosenzweig and Parry (1994).
65. Nordhaus (1991).
66. Downing (1995), Liverman (1992, 1994b), Watts and Bohle (1993).
67. Easterling et al. (1993), Rosenberg et al. (1993).
68. Cohen (1996).
69. Cane et al. (1994).
70. Colwell (1996), McMichael (1996), Patz et al. (1996).
71. Kalkstein (1993, 1995), Kalkstein and Tan (1995).
72. Ortloff and Kolata (1993), Shimata et al. (1991).
73. Lamb (1995), Vickers (1997).
74. Mileti et al. (1995), Wenger (1985), Drabek (1986), Burton et al. (1993), Mileti et al. (1995).
75. Mileti et al. (1995), National Research Council (1999).
76. National Research Council (1996b).
77. Cane et al. (1994).
78. Bentham (1993).
79. E.g., Homer-Dixon (1991), Homer-Dixon et al. (1993), Homer-Dixon and Levy (1995), Myers (1993).
80. E.g., Gleick (1989), Liverman (1994a), Lonergan and Kavanagh (1991).
81. Krasner (1983), Levy et al. (1995), Young (1994a).
82. Regime formation, Young and Osherenko (1993); modes of influence, Haas et al. (1993), Young (1996); financial transfers, Keohane and Levy (1996); policy development, Social Learning Group, (1998); implementation of agreements, Jacobson and Weiss (1990); Victor et al. (1997); analogy between international and local levels, Keohane (1993), Keohane and Ostrom (1995); systems for compliance, Mitchell (1994), Chayes and Chayes (1995).
83. Nichols (1984), Shavell (1985), Tietenberg (1985), Baumol and Oates (1988), Cropper and Oates (1992), Peck (1993), Gardner and Stern (1996).
84. Keohane and Levy (1996).
85. Haas (1990), Thacher (1993), Parson (1993).

86. Haas (1993), Litfin (1994).
87. Social Learning Group (1998).
88. Mitchell (1994), Chayes and Chayes (1995), Victor et al. (1997).
89. March and Olsen (1989), North (1990), Powell and DiMaggio (1991), Scott (1995).
90. Ostrom (1990), Bromley (1992), Baland and Platteau (1996).
91. Groves et al. (1987), North (1990, 1994).
92. Schlager and Ostrom (1992), Hanna and Munasinghe (1995a, b), Hanna (1996).
93. McCay and Acheson (1987), Berkes et al. (1989), Feeny et al. (1990).
94. Levine (1986).
95. Axelrod (1984), McKean (1992), Ostrom et al. (1994).
96. McCay (1995), Young (1994b), Keohane and Ostrom (1995), Renard (1991).
97. Tietenberg (1991).
98. Squires et al. (1995), McCay (1995), Young and McCay (1995).
99. Tietenberg (1985, 1992), Blinder (1987).
100. Described in Hempel (1996).
101. Cropper and Oates (1992).
102. Mitchell and Carson (1989), Kahneman et al. (1993), Portney (1994), Hanemann (1994), Diamond and Hausman (1994).
103. National Research Council (1994a).
104. Keeney and Raiffa (1976), Edwards and Newman (1982), von Winterfeldt and Edwards (1986), Fischhoff et al. (1984), Gregory et al. (1993), Brody and Rosen (1994).
105. Simulations and policy exercises, Brewer (1986), Parson (1996, 1997), Toth (1994); deliberative methods, Renn et al. (1993, 1995), Sagoff (1998).
106. Viscusi and Moore (1989), Cropper et al. (1994).
107. Zeckhauser (1975), Leigh (1989), Ellis (1993).
108. E.g., Fischhoff et al. (1984), Slovic (1987), National Research Council (1989, 1996b), Krimsky and Golding (1992).
109. E.g., Vaughan (1993, 1995), Flynn et al. (1994), Stern et al. (1993), Barke et al. (1997).
110. Fischhoff et al. (1981), National Research Council (1994b, 1996b).
111. National Research Council (1996b).
112. Ibid., Renn et al. (1995), Dietz and Stern (1998).
113. E.g., Jasanoff (1986), Social Learning Group (1998), National Acid Precipitation Assessment Program (1991), Ludwig et al. (1993).
114. Grobecker et al. (1974).
115. Weyant et al. (1996), Parson and Fisher-Vanden (1997).
116. Nordhaus and Yohe (1983).
117. Lave and Dowlatabadi (1993), Morgan and Dowlatabadi (1996).
118. U.S. Environmental Protection Agency (1989), Mintzer (1987), Rotmans (1990).
119. Nordhaus (1994), Peck and Teisberg (1992), Manne et al. (1993), Wigley et al. (1996), Grubb et al. (1995), Hourcade and Chapuis (1995).
120. Models focusing on uncertainties, Morgan and Dowlatabadi (1996), Hope et al. (1993), Tol (1995), van Asselt et al. (1996), models focusing on adaptive strategies, Hammitt et al. (1992), Yohe and Wallace (1996).
121. Alcamo et al. (1994).
122. Claims about market impacts, Mendelsohn and Newman (1998), Weyant et al. (1996), Yohe et al. (1996); claims about costs of abatement paths, Manne et al. (1993), Peck (1993), Nordhaus (1994), Kolstad (1996); claims about high relative costs of immediate action, Hammitt et al. (1992), Richels and Edmonds (1995), Wigley et al. (1996), Yohe and Wallace (1996).
123. Nordhaus and Yohe (1983), Morgan and Dowlatabadi (1996), Yohe and Wallace (1996).
124. Alcamo et al. (1995).

125. Dunlap (1992), Jones and Dunlap (1992), Dunlap et al. (1993), Witherspoon et al. (1995).
126. Dunlap et al. (1993).
127. Inglehart (1995).
128. Stern and Dietz (1994), Kempton et al. (1995).
129. E.g., Rokeach (1973), Schwartz, (1992).
130. E.g., Stern et al. (1993).
131. E.g., confusion with ozone depletion and a strong perceived link to air pollution; Kempton (1991), Löfstedt (1992, 1995).
132. Consumer society debate, Goodwin et al. (1997), Crocker and Linden (1998); emulation debate, Wilk (1997).
133. Stern and Oskamp (1987), Kempton (1993), Lutzenhiser (1993), Gardner and Stern (1996).
134. Political participation, Dunlap and Mertig (1992), Brulle (1995); value priorities, Inglehart (1990, 1997), Stern and Dietz (1994), Kempton et al. (1995); framing of issues, Gamson and Modigliani (1989), Dietz et al. (1989), Mazur and Lee (1993); actions of scientific experts, Haas (1990, 1993).
135. Runge et al. (1994), Runge (1995).
136. Dicken (1992), Featherstone (1990), Sklair (1991).
137. Johnston et al. (1995).
138. Runge et al. (1994), Runge (1995).
139. Johnson and Beaulieu (1996).
140. Appendini and Liverman (1994).
141. de Bardeleben (1985), Vari and Tamas (1993).
142. E.g., Pritchett (1994).
143. See Hayflick (1994) for a summary.
144. Black (1994), El-Hinnawi (1985), Hugo (1996), Wood (1994).
145. Solow (1993), Arrow et al. (1995).
146. Technology diffusion, Grubler (1996); dematerializations and decarbonization, Herman et al. (1989), Wernick and Ausubel (1995), Nakicenovic (1996); time trends, Schurr (1984).
147. Induced innovation, Griliches (1957), Boserup (1965, 1981), Nelson and Winter (1982), Arthur (1994); synthesis, Ruttan (1997).
148. In the United States in 1995 and in Austria in 1997.
149. World Resources Institute (1996).
150. E.g., National Research Council (1992, 1994c, 1997).
151. National Research Council (1997).
152. Stern (1997).
153. National Research Council (1997).
154. National Research Council (1999).
155. Brooks (1986).
156. Kaplan (1994), Myers (1993), Ramlogan (1996); also see note 143.
157. Turner et al. (1995).
158. Turner et al. (1993), Moran (1995), National Research Council (1998).
159. E.g., Mausel et al. (1993), Moran et al. (1994).
160. E.g., experience with TIGER files from the U.S. census, National Research Council (1998).

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8

Observations

INTRODUCTION

The U.S. Global Change Research Program (USGCRP) has responsibilities to observe, document, and understand global change and to predict it to the extent possible. The USGCRP does this by concentrating on five science areas: seasonal-to-interannual variability, decadal-to-centennial variability, atmospheric chemistry and ultraviolet-B radiation, ecosystems, and human dimensions—areas described in the previous chapters. By far the largest share of USGCRP funding goes to making observations to accomplish both the aims of the science areas and those of observing and documenting global change.

This chapter constitutes the link between the scientific foundation established in Chapters 2 through 7 and the course of action now required. The scientific foundation for each of the six primary science areas—biology and biogeochemistry of ecosystems, seasonal-to-interannual climate change, decadal-to-century climate change, atmospheric chemistry, paleoclimate, and the human dimension of global change—consists of a statement of the following: scientific character of the problem, selected case studies, key unanswered scientific questions, lessons learned in the course of scientific research over the past decades, and research imperatives.

The research imperatives are central. They connect theory and observation, defining the specific observations that are required. They connect priorities and resources and science with public policy. They separate, as direct experience has shown, success and failure. Together with consideration of the lessons learned, they establish the foundation for an effective scientific analysis of the Earth system.

Several basic scientific approaches, which set observational demands, can be distinguished: *testing* specific hypotheses—hypotheses that seek to define mechanisms, whether chemical, biological, or physical, that control the Earth system and its climate; *defining* the degree to which the Earth system has changed and is changing over periods of years, decades, centuries, and millennia; and (c) *exploring* largely uncharted regions, which may be defined geographically, mechanistically, or in other scientific terms. In the course of establishing an observational approach it is essential not to lose sight of this distinction.

There are also important distinctions in the required datasets for the different disciplines. These distinctions are the basis of fundamental "cultural" differences in the architectures selected for specific observational approaches. For example, observations are obtained in different ways to address questions about different phenomena, such as the following:

- Ice cover changes as a function of time on seasonal-to-decadal scales.
- Free radicals at the parts-per-trillion level in the troposphere and the stratosphere.
- Vegetation pattern changes in terrestrial systems and oceanic systems.
- Secular trends in atmospheric temperature with an accuracy of 0.1 K, as a function of altitude, latitude, longitude, and season.
- Mesoscale meteorological events tied to global-scale variations such as the El Niño-Southern Oscillation (ENSO).

Observations required for each of these phenomena are not obtainable through a single solution, such as a single global network of ground-based observations or an ensemble of space-based remote sensors. While considerable intrinsic programmatic pressure exists for a "unified" solution to Earth observations, the scientific context speaks strongly for a flexible and adaptive aggregate of techniques that attack specifics, whether of long-term trends or of mechanisms that control the Earth system.

A series of examples in Chapters 2 through 7 also represented a broad spectrum between observational constraint and theoretical speculation. The scientific method is pursued in an effective and vital manner when the fundamental design of the observational approach is matched to the calculated observables such that specific mechanisms, fundamental to the system, are tested directly. Models are very powerful when used in this context (see Chapter 10). They are central partners with observations in the course of proving or disproving fundamental assumptions.

This report approaches the problem of observations as a synthesis, working from scientific research needs to observational implementation. It has always been assumed that building a global observing system would serve the needs of most of the science components of the USGCRP. Indeed, a parallel activity is taking place (Global Climate Observing System, GCOS) to design a global observing system for climate to satisfy both scientific and monitoring needs.[1] Parallel efforts are under way for the ocean (Global Ocean Observing System) and the land surface (Global Terrestrial Observing System); the climate modules of these systems are identical to the ocean and land modules of GCOS. However, it is our impression that there is no guarantee that such an observing system, even if it could be built at this time, would (or could) satisfy research needs. By designing a multiuse observing system for research purposes and then adapting it to meet global observing and monitoring system needs, there is some assurance that both research and monitoring needs will be met in an orderly manner. The model used here depends first on satisfying the needs of the science areas of the USGCRP, transitioning those parts of the system that can be made operational and then seeing how close to a global observing system we have come.

OBSERVATIONS REQUIRED FOR THE SCIENCE ELEMENTS OF THE USGCRP

As stated, the issue of observations is approached here in a synthetic manner. Scientific research needs were examined in Chapters 2 through 7. For each element described in those chapters the observational implications of those research needs are examined. These implications are examined in this section at the level of detail representing the state of the science in each of the subject areas. Given the disciplinary breadth of the USGCRP, the requirements are quite heterogeneous in both content and method of presentation. For example, observational requirements for the Global Ocean-Atmosphere-Land Surface (GOALS) program are detailed in another National Research Council report that is in press and are only summarized here. For other elements, such as the biology and biogeochemistry of ecosystems area, arguments leading to the observational requirements are repeated here for clarity. This chapter is also limited to discussion of observational needs and not the technology to supply those needs.

Of particular interest is the degree of commonality among the observational requirements of the science elements, despite the disciplinary differences. For example, the need to observe radiatively active gases in the atmosphere is common to atmospheric chemistry, ecosystems, and decadal to centennial climate change research areas. Observations of streamflow, atmospheric and sea surface temperatures, and precipitation are emphasized across science elements. These common needs are not necessarily surprising, but they do emphasize the importance of such basic long-term measurements for the disciplines of global change.

Biology and Biogeochemistry of Ecosystems

The Research Imperatives for ecosystems research, as defined in Chapter 2, are:

- *Land surface and climate*. Understand the relationships between land surface processes and weather prediction and between changing land cover and climate change.

- *Biogeochemistry.* Understand the changing global biogeochemical cycles of carbon and nitrogen.
- *Multiple stresses*. Understand the responses of ecosystems to multiple stresses.
- *Biodiversity.* Understand the relationship between changing biological diversity and ecosystem function.

Research on global ecosystem processes motivates four broad classes of observations and experimental studies, shown below. As noted in Chapter 2, large-scale measurements in ecology tend to support all of the research imperatives above in a crosscutting fashion, with any one measurement set helping to test a variety of hypotheses. Ties of these measurement areas to the research imperatives are shown in Table 2.2. The four key measurement areas are time series observations of ecosystem state; land use and land cover change; site-based networks; and measurements of diversity, functional diversity, and ecosystem function.

Time Series Observations of Ecosystem State

Global time series of vegetation and phytoplankton state, derived from the National Oceanic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer (AVHRR) and Coastal Zone Color Scanner sensors, for land and ocean, respectively, have proven their value in understanding the seasonal and spatial characteristics, interannual variability, and trends of large-scale biogeochemistry and biophysical processes.[2] Space-based measurements of ecosystem state are fundamental in determining the link of terrestrial ecosystems to climate, the biogeochemistry of the land and oceans, and the impacts of climate and other disturbances. While measurements of "greenness" and ocean color are not direct ecological properties, they have proven to be highly correlated with spatiotemporal dynamics of ecosystems. Recent work[3] highlights both the utility of these records and the dependence of the science on long and consistent records. Stable calibration and removal of the atmospheric signals of ozone, water vapor, and aerosols are critical to detecting ecological signals. While there is ample room for innovation in land surface remote sensing, stable calibration and correction impose stringent requirements on the sensor or sensors deployed. New instruments, while adding new capabilities, must also be "backwards compatible" to preserve time series. Atmospheric correction requires that coincident observations to quantify water, ozone, and aerosols be available for use in land surface retrieval algorithms. Spatial and temporal resolution for time series instruments are typically a compromise between sufficiently high spatial resolution to resolve ecosystem structure (0.25 to 1 km^2) and swath width and data rate limitations associated with near-daily coverage. High temporal coverage is needed to ensure adequate sampling of seasonality, especially in cloudy environments. These requirements apply generally for both terrestrial and marine ecosystems; marine ecosystems add additional instrument requirements to avoid saturation by sun glint or high reflection. Data for land cover change require higher spatial but lower temporal resolution.

Land Use and Land Cover Change

Changing land use and land cover are fundamental drivers of global change and direct reflections of human activity and impacts. Land use changes have profound effects on the biogeochemistry of carbon, infrared active gases, photochemically active gases, and aerosol production (via dust and biomass burning). Land use changes also affect hydrology and erosion and, by changing surface albedo and energy exchange, can have direct effects on climate. People often create highly heterogeneous landscapes, mosaics that can encompass activities with highly divergent effects on ecological processes. The spatial arrangement of landscapes can affect exchanges of water and associated solutes and particulates in freshwater and coastal margin areas, with land cover at the land-water margins having substantial effects on water chemistry. The arrangement of landscapes also affects biological diversity, invasibility, and extinctions. Data on land cover and its change over time must thus capture the spatial scales of natural and human patterns. Space-borne sensors with resolutions from a few square meters to tens of square meters have proven to meet these needs.[4] Sensors with two to seven spectral bands are adequate for land cover mapping, although new technology employing spectrometers,[5] radar, or lidar has great potential. As in measuring ecosystem state, "backwards compatibility" must be preserved to continue existing time series when new technology and capability are introduced.

Site-Based Networks

In situ measurements of ecological processes tend to be highly multivariate. In terrestrial systems, understanding a measurement of CO_2 flux and determining net primary productivity (NPP) require sampling multiple plant parts (leaves, wood, roots), often of several life forms (e.g., co-occurring grasses, shrubs, and trees). The plant parts are then analyzed for carbon and nitrogen. Understanding spatial variations in gradients of atmospheric CO_2, $^{13}CO_2$, $CO^{18}O$, or O_2 requires a network of measurement sites over large areas. To understand this process, leaf physiology, soil microbial processes, water fluxes, and other variables must be determined. Parallel issues arise in marine ecosystems regarding trophic dynamics and transport. At many sites, measurements are made as part of an experimental design including controls and various manipulations (e.g., of nutrients, species composition, disturbance frequency). These measurements are the essence of ecological data: the satellite and other geographic data serve to knit together disparate process studies in space and time. While there is much interest in a common set of quantities in ecological site studies (quantities such as CO_2, trace gas and water fluxes, NPP, nutrient availability, and species composition and diversity), achieving consensus on a core set of measurements, standard methods, and data formats is just beginning. No global-scale experimental design implementing such sites is in place to sample marine and terrestrial ecosystems, although such a design is proposed by the International Geosphere-Biosphere Programme (IGBP), using long baseline transects across ecological gradients. A high priority of global ecosystem science is to develop a network of appropriately sited atmospheric concentration and isotope, flux, and ecological process sites. Both the overall experimental design and the suite of measurements and methods must be decided. Minimally intrusive measurements (e.g., flux measurements) and manipulations (e.g., of CO_2 concentration) must be components of such a network design.

Recent advances in hyperspectral measurements made directly and remotely have established that remote sensing of foliar chemistry will be an important element in producing large-scale spatially explicit estimates of forest ecosystem function. During the past decade, a number of studies were conducted to determine if data from the National Aeronautic and Space Administration's 10-nm spectral resolution Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) could be used to make canopy nitrogen and lignin measurements. AVIRIS channels in the visible and infrared regions were correlated to field-measured foliar nitrogen and lignin.[6] Estimates of canopy foliar nitrogen were used as input to the primary production model[7] to determine ecosystem productivity at the Harvard Forest, in Massachusetts. At Blackhawk Island, AVIRIS-derived foliar lignin was used to determine nitrogen mineralization rates using a relationship observed by Wessman et al. (1998). These and other results suggest that direct measurement of forest canopy chemistry characteristics, based either on field measurements or via remote sensing, may provide simple, direct scalars of current forest productivity potential. In the coming decade, a space-based system will replace AVRIS, and the application of these techniques can be made at research sites globally.

Measurements of Diversity, Functional Diversity, and Ecosystem Function

The issue of diversity and species composition changes has emerged as a critical topic for global change in recent years. It is clear that the functional diversity of the Earth's biota is a first-order control over global ecosystem function, but how changes to the biota will affect global ecosystem function still is a young research topic.[8] Designing a global observing system and network of experimental studies, analogous to those described above for biogeochemical fluxes, is premature; the necessary monitoring and manipulations at global scales are currently far from obvious. But a major exploratory effort involving manipulations, studies of ecosystem function in the face of ongoing invasions, extinctions, species range shifts, and global monitoring of species diversity, invasion, and extinction rates are all needed. These exploratory studies will lay the groundwork for a more systematic attack. The foundation for systematic study and monitoring of changing diversity and functional diversity must be laid quickly and a global research program put in place.

Key Measurements for Ecosystem Studies

Based on these considerations, the tables below present time- and space scales of critical in situ (Table 8.1) and remotely sensed (Table 8.2) measurements for terrestrial and marine ecosystem studies. These tables present examples of issues, measurements, and timescales, but they are not exhaustive.

Seasonal to Interannual Climate

Chapter 3 sets forth three broad Research Imperatives: ENSO prediction research, global monsoon research, and land surface exchanges, downscaling, and terrestrial hydrology research. These imperatives, as in other chapters, frame the observational requirements.

ENSO Prediction Research Imperative

The ENSO prediction process—predicting aspects of sea surface temperature (SST) and corollary variables—requires data to initialize the coupled models and data to evaluate the skill of the predictions. Because SST is the crucial variable to predict, weekly fields of SST at the $1° \times 1°$ level are absolutely essential. These observations are currently provided by AVHRR, combined with in situ drifters to pin down the absolute values and gradients of SST.

The key variables for initializing the model are the state of the atmosphere and the density state of the upper ocean. The state of the atmosphere does not seem to be as critical for initialization, since the model atmospheric state rapidly adjusts to the initial SST. In any case, the state of the atmosphere is provided by the twice-daily analyses from the operational weather prediction models.

The internal state of the upper ocean can be assessed in two separate ways: directly by temperature-measuring instruments, on a line connecting a surface mooring to a bottom anchor, or indirectly by applying observed heat and momentum fluxes over the ocean component of the coupled model for a long period of time (usually exceeding 20 years). In practice, salinity is very difficult to measure and does not make a major contribution to the initial thermal state, so the direct method measures only temperature. The indirect method depends primarily on measuring the momentum fluxes with the heat fluxes parameterized, so that only the surface winds are used in the calculation.

Currently, ocean models are initialized by combining the two methods above, assimilating both the long-term history of the wind fields and the currently ob-

TABLE 8.1 Time- and Space Scales of Key In Situ Measurements for Terrestrial and Marine Ecosystem Studies

Issue	Measurement	Measured or Inferred Quantities	Temporal Resolution, Duration of Interest	Sampling Strategy	Technology
Changes in climate forcing to ecosystems.	Temperature, precipitation, radiation, wind speed, humidity.	Surface climate.	Daily to weekly, seasonal to interannual.	Major biomes, elevation zones, climate regions, oceans.	Automated or manned stations, data assimilation.
Land surface effects on physical climate.	Water, CO_2, heat, momentum fluxes, net radiation.	Evapotranspiration, sensible heat, albedo.	Daily to weekly, seasonal to interannual.	Major biomes with replication along climate gradients within biomes.	Eddy covariance, micrometeorology.
Land surface effects on global hydrological cycle and the climate system.	Streamflow.	Runoff, water balance, freshwater inputs to oceans.	Daily to weekly, seasonal to interannual.	Major biomes with replication along climate gradients within biomes.	Gauged watersheds, major rivers.
Spatial-temporal effects of climate and ocean circulation and mixing on carbon fixation.	Water (on land), nutrients (land and sea), CO_2, heat and momentum fluxes, net radiation.	Net ecosystem exchange, carbon balance, CO_2 flux-climate relationships.	Daily to weekly, seasonal to interannual.	Major biomes with replication along climate gradients within biomes; ocean regions.	Eddy covariance, micrometeorology on land, short-term assays in marine and aquatic systems.

TABLE 8.1 Continued

Issue	Measurement	Measured or Inferred Quantities	Temporal Resolution, Duration of Interest	Sampling Strategy	Technology
Spatialt-temporal changes to the nitrogen cycle.	Nitrogen gas emissions and deposition.	Nitrogen inputs and losses, emission of chemically active species.	Daily to weekly, seasonal to interannual.	Major biomes with replication along climate gradients within biomes; ocean regions.	Eddy covariance, eddy accumulation, chamber measurements, concentration profiles.
Spatial-temporal changes to nutrients in aquatic systems.	Streamwater nutrient and organic matter concentrations and estuarine fluxes.	Nitrogen losses from terrestrial systems, terrestrial inputs to the oceans.	Daily to weekly, seasonal to interannual.	Major watersheds.	Gauged watersheds, concentration measurements of solutes.
Changes in pollution inputs to ecosystems.	Nitrogen, sulfur, ozone deposition.	Nitrogen, sulfur, acidity, ozone stress.	Daily to weekly, seasonal to interannual.	Major biomes and airsheds, ocean regions.	Eddy covariance, eddy accumulation.
Increasing CO_2 effects on ecosystem processes.	CO_2 enrichment experiments.	Response of ecosystem function and carbon storage to increasing CO.	Daily to weekly, seasonal to interannual.	Major biomes with replication along climate gradients in biomes.	Open-topped chambers, free air CO_2 enrichment.

TABLE 8.2 Time- and Space Scales for Key Remotely Sensed Observations for Ecosystems Studies

Research Area	Measured or Inferred Quantities	Temporal Resolution, Duration of Interest	Spatial Resolution and Coverage	Technology
Vegetation feedbacks to climate.	Leaf area, light intercepted by foliage and, by inference, evapotranspiration.	Daily to weekly, seasonal to interannual.	0.25 to 1 km^2, globally.	Optical remote sensing, radiometry.
Climate variability trends and vegetation response.	Leaf area, light intercepted for photosynthesis and, by inference, primary productivity.	Daily to weekly, interannual to decadal.	0.25 to 1 km^2, globally.	Optical remote sensing, radiometry.
Land cover change.	Ecosystem type (forests, grasslands, agriculture) over time and, by inference, rates of land use change needed for calculating changes to ecosystem-atmosphere fluxes (CO_2, H_2O, N_2O).	Seasonal, decadal.	1 to 100 m^2, regional to global.	Optical radiometry or spectroscopy, possibly radar or lidar in the future.
Ocean color.	Phytoplankton abundance and, by inference, marine primary productivity.	Daily to weekly, seasonal to decadal.	1 km^2, global oceans.	Optical radiometer.

tained thermal state of the upper ocean, to arrive at an optimal estimate of the ocean's current thermal state. The subsurface ocean data are provided by a network of 70 moored TAO (tropical atmosphere-ocean) arrays in the tropical Pacific Ocean (providing approximately 2° of meridional resolution and 15° of longitudinal resolution) and by the ongoing XBT network. These same moorings measure winds, but, since the full TAO array has been in existence for only two years or so, historical winds must be obtained from the Comprehensive Ocean-Atmosphere Data Set, gathered from individual ship reports from volunteer observing ships.

Because the ENSO observing system described in Chapter 3 measures the quantities needed to initialize the ocean component of the predictions, it is vital that this array be continued. The ENSO observing system was designed on the basis of the scales of variability of the winds. It may turn out that either fewer or more moorings are required to optimize prediction skill.

Other quantities also prove useful for initialization:

- Sea surface height, as measured by satellite altimetry and tide gauge stations scattered around the islands and coasts of the tropical Pacific.
- Currents measured on the equator where geostrophy is more problematic.
- Cloud cover and solar irradiance reaching the surface.
- Precipitation in those areas in and surrounding the tropical Pacific (and remotely in the areas that ENSO affects) to evaluate the skill of precipitation predictions.
- Upper-level water vapor to evaluate the effect of seasonal to interannual variability, as opposed to greenhouse feedback, of this quantity.

The overall recommendation, therefore, is to maintain global SST measurements and maintain the ENSO observing system, especially the TAO array.

Global Monsoon Research Imperative

The GOALS program has devoted much effort to defining the observational requirements for global seasonal to interannual predictions. These requirements are summarized in Table 8.3. Note that variables are listed in priority order. Not surprisingly, there is virtually complete overlap between these variables and those identified as important in pursuing the other seasonal to interannual research imperatives identified in the following section. Only the variable of land surface energy fluxes is not identified both below and in the following section.

Land Surface Exchanges, Downscaling, and Terrestrial Hydrology Research Imperatives

The primarily hydrological observational datasets needed to support research imperatives in the areas of land surface exchanges, downscaling, and terrestrial hydrology can be described as follows.

TABLE 8.3 State and External (or Forcing) Variables* That Must Be Measured for the GOALS Program

Realm	State Variables	External Variables
Ocean	• Upper-ocean temperature • Upper-ocean currents • Sea level • Upper-ocean salinity • Optical absorption • Sea ice extent, concentration, and thickness	• Wind stress • Net surface solar radiation • Downwelling longwave radiation • Surface air temperature • Surface humidity • Precipitation
Atmosphere	• Wind structure • Thermal structure • Surface air temperature • Sea level pressure • Water vapor structure • Columnar water vapor and liquid water content • Cloud cover and height	• Sea surface temperature • Net radiation at top of the atmosphere • Land surface variables (see below)
Land	• Soil moisture • Snow cover and depth • Vegetation type, biomass, and vigor • Water runoff • Ground temperature	• Precipitation • Net surface longwave and short wave radiation • Surface wind • Surface air temperature • Surface humidity • Evaporation • Evapotranspiration

* State variables are defined as variables necessary to monitor the "state" of the physical system or subsystem, while "external" or "forcing" variables are those variables that define the degree of interaction between system components (NRC, 1998a). SOURCE: NRC (1998a).

Streamflow

At the same time that the policy-making community seeks guidance and advice on interpreting the impact of global hydrological change, the basic monitoring of hydrological fluxes, through data provided by observational networks for discharge and water quality, remains fragmented at best. Developing regions of the world, by their very nature subject to the direct and immediate effects of rapid anthropogenic change, lack the infrastructure to adequately monitor the status of their water resources. Even in traditionally well-monitored regions such as the United States, there has been a substantial decline in land-based monitoring capacity.[9] In addition, there has been an assault on open access to basic hydrometeorological datasets for global change research, aided in large measure by commercialization.[10] The World Meteorological Organization's Global Runoff Data Center in Koblenz, Germany, holds information on nearly 3,000 discharge monitoring stations. However, in accordance with the wishes of the donor nations, access to this information is restricted and no transfer of the complete global dataset or substantial portions of it are possible. A recent UNESCO (United Nations Educational, Scientific, and Cultural Organization) publication and related digital data bank of approximately 1,000 discharge monitoring stations[11] represents the last digitized global data bank of river runoff that is freely available to the global change community (at Oak Ridge National Laboratory Data Acquisition and Archive Center). Lamentably, its last data entry is for 1991.

A set of long-term index stations should be identified, some of which should be as free from the effects of upstream regulation and diversions as possible. In the United States the logical responsible agency would be the U.S. Geological Survey (USGS). However, the funding method currently used for the USGS stream gauge network is not necessarily consistent with the needs of a climate network (e.g., only about 10 percent of USGS stations are funded from the agency's core funds; the remainder are funded cooperatively with state agencies and by other federal agencies for operational purposes). Moreover, there is a significant need for this information on a global scale, which poses a difficult operational and political challenge. This topic of in situ riverine information is important and should be addressed.

Precipitation

Station data. The United States must maintain existing long-term stations within the National Climatic Data Center (NCDC) cooperative network, particularly the subset of stations that make up the Hydroclimatic Data Network and the U.S. Historical Climate Network. Precipitation measured at first-order stations has recently undergone radical changes and considerable technical problems, making these networks even more important.

Radar precipitation data. The National Center for Environmental Prediction has recently started to archive a merged WSR88-D (Doppler radar)/gauge product (4-km resolution) that covers most of the United States. The suitability of these data for climatological purposes needs to be evaluated, and steps must be taken to ensure the security of the long-term archive of the data and to ensure that the data are freely available to the scientific community. From a more global perspective, the recent Tropical Rainfall Measurement Mission (TRMM) launch holds great promise for tropical regions.

Surface Radiation

Only a very small number of stations now operate in the continental United States that collect a full suite of surface radiation observations (the SURFRAD network). The adequacy of this network for studies of seasonal to interannual variability should be evaluated.

Snow

Point observations. Prior to the recent National Weather Service (NWS) modernization, snow water equivalent point observations were collected across the United States at NWS stations and archived at the NCDC. Since NWS's modernization, snow water equivalent measurements are only monitored at selected NWS forecast offices and are now considered supplementary data. This has significantly decreased data coverage.

Snow water equivalent point observations are collected primarily at Natural Resources Conservation Service Snow Telemetry sites in mountainous areas of the western United States. The suitability of these sites for long-term climate studies needs to be evaluated (the longest records from these stations date only to the mid-1980s). Snow depth measurements are collected at a few thousand NCDC cooperative stations. The feasibility of using some subset of these stations to measure snow water equivalent should be evaluated. The objective is to achieve a much more uniform spatial distribution of station-based observations.

Areal extent. The NOAA National Operational Hydrological Remote Sensing Center and the National Environmental Satellite, Data, and Information Service (among other entities) produce satellite-based snow areal extent measurements of the continental United States and the world. These products are currently used for operational purposes but could prove extremely valuable for assessing such interactions as those between the continental extent of seasonal snow cover and large-area circulation patterns. Steps should be taken to ensure that these data are climatologically useful.

Algorithms. Satellite remote sensing algorithms to estimate snow water equivalent in a manner suitable for global studies (e.g., spatial resolutions of tens of kilometers) have been improved and may be suitable for seasonal to interannual timescale studies, notwithstanding problems remaining for forested areas. These products need to be assessed and archived at (or through) the National Snow and Ice Data Center.

Wind and Humidity

Although wind and humidity data are collected at NCDC surface airways stations, many of the records are affected by station and instrument changes, and their use for climatological purposes is problematic. Nonetheless, they are critical for computing potential evapotranspiration, and they provide reference values for approaches that can lead to spatial estimates (e.g., modeling combined with atmospheric profile data or analysis fields). Thus, more attention should be given to the climatological value of these observations. On global scales it would be extremely useful if a far richer network of wind observations, particularly over oceans, could be achieved.

Surface Air and Skin Temperature

Observations of surface air temperature are critically important to predict evapotranspiration and snow accumulation and melt. Surface air temperature measurements are routinely collected at NCDC cooperative observer stations, as well as NWS manned observing stations. Because air temperature tends to have much higher spatial correlation locally than, for instance, precipitation, maintenance of an adequate station precipitation network should assure adequacy of surface air temperature measurements, provided that these variables are coincidentally collected. Direct observations of surface (skin) temperature are much more problematic. Surface observations have generally only been collected in research projects and are difficult to interpret. Nonetheless, skin temperature is a state variable predicted by most land surface schemes (some schemes predict an effective vegetation temperature as well). Thus, these measurements might be updated also. Satellite sensors and algorithms can produce global estimates of skin temperature at time frequencies as high as daily; a ground network could play a critical role in validating and calibrating the long-term spatial records that are now being acquired. The role of Earth Observing System (EOS) PM-1 and subsequently the temperature sounding made by the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) should be particularly valuable; however, there must be a consistent connection between EOS and NPOESS (and the European system of polar-orbiting platforms).

Surface Energy Fluxes

Direct observations of surface energy fluxes (latent, sensible, and ground heat flux) have been collected almost exclusively in conjunction with research programs (e.g., the First International Land Surface Climatology Project Field Experiment, the Hydrological and Atmospheric Pilot Experiment). Recent advances in instrumentation may permit routine long-term operation of eddy correlation and other systems. A commitment has been made, for example, to continue long-term operation of some of the Boreal Ecosystem-Atmosphere Study tower flux sites. The feasibility of long-term operation of surface flux sites should be assessed to represent such features as major vegetation types in the United States and perhaps globally.

Soil Moisture

Soil moisture plays a key role in partitioning net radiation into latent, sensible, and ground heat fluxes, particularly in summer. Many studies have indicated the potential importance of feedbacks between soil moisture and climate, especially in the interior of the northern hemisphere continents in summer. Therefore, observation of soil moisture is of great importance, through ground- or satellite-based observing systems or both. A few networks in the continental United States collect ground-based point observations of soil moisture, including networks of the Illinois Water Survey and the Oklahoma Mesonet. While there are questions about how point observations of soil moisture can be interpreted in the context of small-scale spatial variability and about the lack of standard instruments, synoptic-scale events are well captured. With regard to remote sensing, both active and passive microwave sensors have shown potential in estimating near-surface soil moisture. Furthermore, in combination with modeling, these surface observations might be extended to greater depth. Many issues remain, and problems of soil moisture estimation from satellite sensors are themselves the subject of ongoing research. Nonetheless, the success of these efforts is critically important for seasonal to interannual prediction and should be highlighted.

Vegetation

Knowledge of seasonal and interannual variability in vegetation properties is critical to understanding links between the land surface and climate at seasonal to interannual timescales. Satellite-based estimates of vegetation properties, such as leaf area index and greenness, are now fairly widely used in numerical weather prediction models. EOS-era developments (e.g., the Moderate Resolution Imaging Spectroradiometer, MODIS) will almost certainly improve the quality of these products. Again, however, it is essential that a consistent transfer of observing be achieved as we move from NASA (morning and afternoon observations from MODIS) to NOAA and EUMETSAT (European Organization for the Exploitation of Meteorological Satellites)-provided observations. There must be sufficient stability and accuracy in the operational instruments to maintain the time series begun by MODIS, and there must be adequate instrumental overlap to ensure that the operational measurement systems are calibrated against the EOS measurements. Furthermore, a long-term global archive of seasonal variations in vegetation properties must be preserved, along with sufficient metadata to resolve questions about any effects of changes in instruments.

Decadal to Centennial Climate Change

The following Research Imperatives (Chapter 4) are required to advance most efficiently our understanding of decadal to centennial (dec-cen) climate variability and change.

- *Natural climate patterns.* Improve knowledge of decade-to-century-scale natural climate patterns, their distributions in time and space, optimal characterization, mechanistic controls, feedbacks, and sensitivities, including their interactions with, and responses to, anthropogenic climate change.

- *Climate system components*. Address those issues whose resolution will most efficiently and significantly advance our understanding of decade-to-century-scale climate variability for specific components of the climate system.
- *Anthropogenic perturbation*. Improve understanding of the long-term responses of the climate system to the anthropogenic addition of radiatively active constituents to the atmosphere and devise methods of detecting anthropogenic phenomena against the background of natural decade-to-century-scale climate variability.
- *Paleorecord.* Extend the climate record back through data archeology and paleoclimate records for time series long enough to provide researchers a better database with which to analyze decade-to-century-scale patterns, specifically to achieve a better understanding of the nature and range of natural variability over these timescales.
- *Long-term observational system*. Ensure the existence of a long-term observing system for a more definitive observational foundation to evaluate decade-to-century-scale variability and change. Ensure that the system includes observations of key state variables as well as external forcings.

The foundation for recent progress in ENSO research was laid by careful diagnosis of ENSO pattern variability (see Chapter 3).[12] Similarly, understanding and predicting decadal-to-centennial (dec-cen) variability to a large extent depend on knowledge of climate patterns on these longer timescales. Logically, we might expect that the response of the Earth system to anthropogenic forcing would be manifested in and/or obscured by these patterns. Thus, one particular important concern is the interactions between natural variability and anthropogenic change.

For greater predictive capability it is essential to understand those processes operating in the various components of the climate system that are relevant to dec-cen variability. Because of the difficulty of directly observing phenomena of interest in dec-cen studies, in contrast to weather or seasonal to interannual studies, the importance of component process understanding is magnified.

With respect to anthropogenic perturbation, it is particularly important to closely monitor the rate and distribution of source functions of the radiatively active gases being added to the atmosphere. These external forcings, which cannot be readily predicted, can then be properly introduced and diagnosed in the predictive model studies. Such models are the primary available means for forecasting anthropogenic change and for guiding diagnostic and attribution studies and sampling efforts. It is therefore critical to adopt an incremental long-term observing system whose characteristics and targeted variables can evolve in parallel with our rapidly improving understanding. The importance of a comprehensive long-term observing system has been endorced by several international bodies, including the World Climate Research Program (WCRP) (see Box 8.1).

Many of the issues defined here require observing systems that do not yet exist or to which no long-term commitment has yet been made. An example is the need to monitor solar irradiance: current data have come from relatively short-term satellite missions that have no operational (long-term) mandate (see the case study later in this chapter). Measurements from different missions observing simultaneously are in significant disagreement, and the magnitude of the offset is of the same order as greenhouse forcing. Addressing decadal-to-centennial solar variability, as discussed above, requires a plan for long-term calibrated solar irradiance measurements across the solar spectrum.

BOX 8.1
WCRP Message to the Conferences of the Parties to the United Nations Framework Convention on Climate Change and United Nations Convention to Combat Desertification

"Well over 300 members of the climate research and policy communities present at the Conference on the World Climate Research Programme (WCRP) (Geneva, Switzerland, 26-28 August 1997) agreed that comprehensive observations of the climate system are critical and noted with concern the decline in conventional observation networks in some regions. This is a serious threat to continuing progress in climate research, and to detection of climate change and attribution of its causes. Without action to reverse this decline and develop the Global Climate Observation System, the ability to characterize climate change and variations over the next 25 years will be even less than during the past quarter century. In some regions, for example, drought-prone parts of Africa, climate change detection, prediction of seasonal and long term variations and reliable assessment of climate impacts could become impossible.

Recognizing the obligations of the Parties to the United Nations Framework Convention on Climate Change under Article 4.1 (g) and (h) (Commitments) and Article 5 (Research and Systematic Observations), we strongly urge that, at the coming sessions of the Conference of Parties, arrangements be put in place to ensure funding and support for the essential observation networks of the Global Climate Observing System (GCOS) and its oceanographic and terrestrial counterparts [Global Ocean Observing System (GOOS) and Global Terrestrial Observing System (GTOS)], and for research involving data interpretation and analysis, as well as for retrieval and preservation of historic data in electronic form.

Without such support, future assessment reports of the Intergovernmental Panel on Climate Change (IPCC), which draw heavily on WCRP research and on the observational data sets, will be significantly compromised."

Finally, as previously indicated, dec-cen research is in its early stages, with new insights, findings, and directions arising rapidly. The long-term sampling strategy and optimal measurement set is evolving with these advances as well. At this stage, then, it is imperative that we begin (or in a few cases continue) consistent monitoring of the most fundamental state variables (e.g., atmospheric temperature and moisture profiles, ocean surface temperature and salinity values) and monitoring of those variables specifically relevant to climate system components to initialize (including via assimilation), force, and diagnose model components and variables.

Atmospheric Observations

The Physical System

The physical state of the atmosphere, regardless of the mechanisms influencing this state, is at the very core of what we call climate. Atmospheric temperature and moisture content, pressure, winds, and cloud cover (the main factor controlling the surface radiation balance) must all be monitored. The spatial distribution of this monitoring can be improved with time to span the globe eventually at the relevant spatial scales, but initially a concerted effort must be made to monitor those variables at current weather station locations.

As the concentration of greenhouse gases increases in the atmosphere, the atmosphere clearly must respond in some manner to accommodate the change in radiative forcing. The atmosphere may respond by warming to some degree, it may change its vertical distribution of moisture and cloud cover, or some combination of these. All of the state variables must be monitored, including their vertical distributions through the troposphere and lower stratosphere, to evaluate the nature of anthropogenic and natural changes. One of the most hotly debated topics in modern climatology is how atmospheric moisture distribution will change in response to the addition of greenhouse gases and therefore whether, or by how much, this moisture response will moderate the temperature response. Thus, it is not enough to measure temperature simply because temperature has been the initial focus of the greenhouse debate.

Atmospheric observations must be collocated with those stations established to monitor surface conditions. This need directly follows from the fact that most, if not all, dec-cen atmospheric variability and change are in response to changes in slower components of the climate system, such as land, ice, and ocean. These components represent the lower boundary of the atmosphere. In many cases, atmospheric changes strongly covary with changes at the surface. To evaluate, diagnose, and attribute dec-cen change, such covariation must be captured in a manner that facilitates analysis and evaluation of hypotheses that describe the coupled mechanisms driving and modulating long-term variability.

Process studies and related field efforts must be directed to improving our understanding and parameterization of surface-atmosphere interaction. Obviously, it is through this boundary interaction that slower-scale components communicate their influences to the atmosphere. Appropriate parameterization of these phenomena is therefore essential, since modeling efforts are the primary tool we have for forecasting future change. We also need better parameterization of clouds, including their distribution and feedback processes, because their treatment in models may prove crucial in predicting long-term climate responses to changes in radiative forcing, as well as other feedback influences associated with variability and change. These parameterizations are currently a primary limitation in existing models.

The Chemical System

The radiative effects of aerosols, direct and indirect, are poorly constrained. Cloud processes, although they occur on far shorter than decadal timescales, are a major uncertainty in predicting future radiation balances. Parameterizations need to be improved.

Carbon cycle questions require a CO_2 measurement strategy that accounts for the hierarchy of scales, both temporal and spatial, inherent in ecosystem processes and their controls. Atmospheric concentration data must allow the identification and quantification of regional sources and sinks and their responses to climate fluctuations and human perturbations. This information will permit integration over regional scales of fluxes and feedback processes that can be measured, understood, and modeled on smaller spatial and temporal scales. Isotopic data allow distinguishing between oceanic and biospheric sinks on regional scales and have provided significant insight into the regional carbon balance. Ratios of O_2 to N_2 in the global atmosphere provide an independent constraint on the balance between net terrestrial and oceanic sinks. The same scaling and measurement issues are almost identical for N_2O and CH_4, and their biogeochemical budgets can be tackled together with a measurement program suitable for CO_2.

Enormous progress in assessing trace gas budgets could be achieved if a method could be developed or refined to directly measure air-sea gas exchange rates. Promising methods are air measurements with eddy correlation and/or eddy accumulation. Such measurements would eventually lead to a realistic understanding of the processes controlling the rate of gas exchange and therefore to a parameterization that could be applied with confidence worldwide. Existing climatologies of the partial pressure differences between the air and the water for many gases could then be turned into maps of gas exchange, making oceanic data into a much more compelling constraint on the atmospheric budget and closing the open boundary of surface oceanic gas budgets.

Ocean Observations

Various types of ocean observations are needed to study the dec-cen variability associated with the primary known patterns of atmospheric climate variability: periodic (decadal) temperature, salinity, oxygen, and tracer sections; velocity profile surveys and repeat sections (starting with World Ocean Circulation Experiment sections); and higher-frequency time series stations (starting with past and present weather ship stations). These measurements will allow better quantitative description of the ocean's participation in dec-cen variability, especially in light of the slowly propagating SST and subsurface anomalies that have revealed the ocean's dec-cen variability as more than stationary patterns. We must extend these surveys into southern hemisphere regions as the nature of the dec-cen variability begins to be revealed.

These sections and time series stations provide the baseline against which the long-term response and change of the ocean can be measured, and they provide the basic observational set from which serendipitous discoveries about the ocean's role in climate change have been realized. In addition, the time series data have been invaluable in studying the ocean's response to atmospheric forcing and its feedback to the atmosphere. These findings are of particular importance because surface layer interaction and response dictate the volume of water in direct communication with the atmosphere. Even a small change in this volume can lead to a significant change in SST, given the same magnitude of surface forcing. The time series stations are the only series available that allow appropriate development, diagnosis, and improvement of these parameterizations.

Continued satellite data are needed for global coverage of sea surface height, SST, winds, and ocean color, but for these data to be useful, corresponding ground-truth ocean observations also are needed. Particular data of interest concern the heat budget. A concerted effort is required to improve estimates of heat flux divergence and heat storage and their variabilities from subsurface ocean data, eliminating disparities between those estimates and air-sea heat exchange estimates. Various subsurface floats and moorings are particularly helpful to supplement shipboard measurements for this study.

Sea level change is another important observational challenge. The Intergovernmental Panel on Climate Change (1996) estimates that sea level in the year 2100 will be 46 to 72 cm higher than today (36 to 53 cm when the effects of sulfate aerosols are included). A range is given because each projection presumes a specific scenario for increase in greenhouse gasses. To validate these predictions, better monitoring of global sea level change and its components will be needed. The prospects for sea level monitoring are good. A global network of sea level stations (Global Sea Level Observing System) is being implemented. Land movements will be measured at some of these stations with satellite geodesy and gravimetric techniques. Satellite altimetry is another important tool coming into use to measure global sea level rise.

Cryosphere Observations

Critical cryosphere-related observations for climate patterns on decadal to centennial timescales include long-term monitoring of surface salinity along with SST, since salinity represents the dominant control on the density of seawater in high-latitude regions. Also, measurements of the sea ice fields themselves, including motion fields and ice thickness, are required to determine the freshwater transports and buoyancy fluxes associated with the ice fields. This freshwater transport has been implicated in driving major changes, even mode shifts in the global thermohaline circulation. Finally, consistent monitoring of iceberg calving and an observational system for determining ice basal melt or growth (e.g., through temperature/salinity moorings across the floating ice shelves) must be established to better determine the freshwater budget. Both field and satellite studies are needed to refine the mass budgets of the Greenland and Antarctic ice sheets. Onsite studies that have focused on ice flow, melting, and calving should be continued and extended. Water vapor flux divergence observations will help pin down the source of the ice sheets' mass. A laser altimeter on a polar-orbiting satellite is needed to augment existing radar altimetry. These satellite data will provide accurate estimates of ice sheet volume and give early warning of possible ice sheet collapse. As in the case of ice, the distribution of snow fields, including thickness and spatial extent, must be monitored. The response of snow distribution to climate change has been hypothesized as being important in surface-climate feedbacks as well as in climate change diagnostics.

Finally, the ocean-atmosphere-ice interaction, particularly the ice or snow surface energy balance (including surface albedo and ocean-ice, ice-cloud, and snow-cloud feedbacks), must be addressed through detailed process studies to improve parameterizations of these processes in climate models.

Land and Vegetation Observations

Observations of changes in land surface characteristics, including surface vegetation, are essential for research goals in both ecosystems and dec-cen climate. Observational requirements are discussed in detail in the section on ecosystems earlier in this chapter. Changes in land surface properties alter not only the distribution of surface reservoirs and the surface-atmosphere exchange of radiatively active gases but also albedo and even surface stress and evapotranspiration efficiency, and the last two both influence the hydrological cycle. This serves as an external forcing to the planet that cannot be predicted and must be introduced into the models as they occur to properly maintain the models' surface forcing conditions.

Long-term monitoring of near-surface aerosol distributions is also needed; these distributions may induce stationary changes in the surface radiation balance, which may lead to large-scale circulation moderation through stable gradient perturbations.

Hydrological Observations

Precipitation is the key hydrological variable. For most studies of dec-cen variability and its effects, global fields of precipitation over timescales of 10 to 100 years are essential. We have no such global instrumental records currently. TRMM is an important first step, but global data are needed. To relate precipitation to global boundary conditions, it is necessary to simultaneously measure SST, vegetative ground cover and soil moisture, and sea and land ice and snow. Nearly every theory of anthropogenic warming finds an increased rate of the hydrological cycle and possible alteration of atmospheric distributions of moisture and of the frequency, intensity, and distribution of rainfall (including severe rainfall events). Thus, monitoring of the surface distribution of precipitation and evaporation must begin. This monitoring includes that over the oceans, where changes in the precipitation minus evaporation balance alter the surface salinity budget, which in high latitudes has been implicated in altering the thermohaline circulation (and driving internal oscillations on dec-cen timescales in ocean models).

Atmospheric Chemistry

Four primary Research Imperatives set the observational demands for this area:

- Secular trends in the intensity of ultraviolet radiation that the Earth receives.
- Source molecules for climate change.
- Secular trends in photochemical oxidants.
- Aerosol radiative forcing and climate change.

Stratospheric Ozone and Ultraviolet Radiation Research Imperative

A central issue of atmospheric chemistry is to define and predict fluctuations and secular trends in the intensity of ultraviolet radiation that the Earth receives. Along with temporal trends in ultraviolet intensity reaching the ground, it is also imperative to address the mechanisms and processes responsible for controlling the transport, photochemical production, and catalytic loss of ozone in the global stratosphere. (The issue of tropospheric ozone is treated below.) The observational priorities in this area, therefore, are observed changes in column ozone itself, transport of chemical species, photochemical transformations, and fundamental laboratory diagnostics of molecular processes.

Define the Intensity of Ultraviolet Radiation that the Earth Receives

Priority: Observe the total column density of ozone from orbit with daily global coverage and accuracy of ±5 percent, such that an uninterrupted record is sustained. These observations must have a precision adequate to detect a trend of 1.5 percent change per decade. Observe the concentration of ozone with altitude resolution of 3 km between 10 and 25 km, such that secular trends in upper-tropospheric and lower-stratospheric ozone can be tracked with an accuracy of 3 percent per decade. From the ground, obtain observations of ultraviolet-B flux, accurate to ±2 percent and precise to ±1 percent at 30 stations worldwide, strategically placed, with 20 in the northern hemisphere, and 10 in the southern hemisphere.

Predict Fluctuations and Secular Trends in Ultraviolet Radiation

Priority: Determine, via tracer and meteorological observations, the residence time and trajectories of air parcels at different altitudes, latitudes, and seasons in the stratosphere, using tracers CO, SF_6, CFC-11, N_2O, N_2, CO_2, O_3, NO_y, and H_2O, obtained simultaneously, with spatial resolution of 0.1 km, accuracy of ±2 percent, precision of ±1 percent, and a grid size the same as spatial resolution.

Priority: Determine the mechanisms responsible for exchange of material between the troposphere and stratosphere. Understanding of the exchange of mass and chemical constituents between the stratosphere and troposphere is essential for identifying the relevant chemical processes and relationships among chemistry, dynamics, and radiation that dominate processes in both the stratosphere and the troposphere. Significant progress has occurred in the theory of stratosphere-troposphere exchange in the past several years,[13] but this advance has served primarily to clarify what must be done to analyze this key transitional region scientifically and to demonstrate that further progress will depend largely on critical observations, particularly in the tropics. Such observations will require high spatial resolution (0.1 km in horizontal and vertical) simultaneous measurements of H_2O resolved into its three phases and the isotopes of H_2O, O_3, CO_2, CO, N_2O, CH_4, upward- and downward-looking lidar for detection of aerosols and cirrus, the upward and downward radiance in the visible and infrared at 1 cm^{-1} spectral resolution with the ability to scan the view direction to any angle in the plane perpendicular to the platform velocity vector, solar tracking that allows absorption measurements in the visible and infrared, upward- and downward-looking polarimetry, microwave temperature profiling above and below the platform, and simultaneous observations of meteorological fields and a complete suite of particle measurements. These observations must be focused first in the tropics, using long-duration (24- to 40-hour) trajectories that span the altitude region from 10 to 22 km, which can lock to surfaces of constant potential temperature (constant entropy) and then to surfaces of maximum gradient in species such as CO observed in real time.

Priority: Determine the destruction rates for ozone in the stratosphere as a function of altitude, latitude, and season by observation of the rate-limiting radicals (NO_2, NO, HO_2, OH, ClO, BrO) and determine the response of the atmosphere to imposed changes by obtaining the derivative of each rate-limiting radical with respect to changes in nitrogen, hydrogen, chlorine, bromine, aerosol reactive surface area, water vapor, and temperature through 80 percent of the ozone column (i.e., up to 26 to 28 km). This goal requires simultaneous observations of reservoir species ($HONO_2$, N_2O_2, $ClONO_2$, HCl, H_2O, $BrONO_2$), long-lived tracers (CO_2, N_2O, CH_4, SF_6, chlorofluorocarbons [CFCs], CO), ultraviolet fluxes into the volume element observed, infrared radiance and flux, particle number, surface area and mass as a function of size, chemical composition as a function of size, and meteorological variables, including pressure, temperature, wind velocity, potential temperature, and potential vorticity. As described in Chapter 5, these observations must be obtained with a spatial resolution of 0.1 km, with simultaneous observation of tracers, reservoir species, and ultraviolet flux. It is critical to extend these observations to extreme conditions, such as the polar winter and tropical tropopause. The accuracy of these observations should be ±5 percent for radicals and ±1 percent for tracers. Grid size should be the same as spatial resolution.

Priority: Make observations of the Arctic. In the past five years the loss of ozone in the late-winter/early-spring Arctic vortex has grown rapidly worse, reaching levels of depletion approaching 30 percent in column ozone, as discussed in Chapter 3. This observed behavior is similar to that of the Antarctic in the early 1980s. Analysis of the cause of this rapid erosion requires high-resolution observations (0.1 km in the horizontal and vertical) between the altitudes of 10 and 25 km of radical and reservoir species (OH, HO_2, NO, NO_2, NO_2, Cl, ClO, BrO, $ClONO_2$, ClOOCl, HCl, $HONO_2$, N_2O_5, H_2O, O_3); tracers (CO_2, CO, N_2O, CH_4, CFCs, SF_6, NO_y); aerosol and particle composition, surface area, and mass as a function of size; spectrally resolved upwelling and downwelling radiation in the ultraviolet, visible, and infrared; continuous absorption measurements in the ultraviolet, visible, and infrared ranges by tracking of the Sun from the platform; and microwave temperature profiling above and below the platform. The trajectories of the experiments are critical. The platform must operate for long durations (24 to 40 hours) in regions of very cold temperatures (down to 170 K) under nighttime conditions and must follow Lagrangian trajectories through the cooling and warming cycles of the volume element on surfaces of constant potential temperature. The data analysis must be executed in real time and used to direct the aircraft trajectory.

Priority: Determine by a combination of laboratory and in situ observations the mechanisms and rates for the homogenous and heterogeneous chemical reactions and the photolysis processes that dictate the rates of chemical transformation in the stratosphere.

Greenhouse Gases Research Imperative

A dominant issue for global change is to characterize the origin, transformation, and removal of infrared active species in the atmosphere, the source molecules for climate change, requiring the following observations.

Priority: Determine the flux of CO_2 from the primary systems (ocean, tropical, temperate, high-latitude terrestrial, Arctic, Antarctic, industrial, agricultural) as a function of season, with spatial resolution of 0.5 km. Grid density is a function of region. Over oceans, ice sheets, and arid regions, resolution should be 50 km in the horizontal, with monthly sampling, except for over the oceans, which should be sampled weekly. Tropical regions should be sampled at 10-km horizontal resolution monthly, except during transition seasons. Industrial regions should be sampled at 5-km horizontal resolution twice monthly. Vertical resolution should be 1 km in all regions.

Priority: Determine the concentrations of CO_2, CH_4 (including its carbon isotopes), O_2, and tracers from ground level to the tropopause as a function of latitude, altitude, and season over each of the primary regions of the globe (oceans, jungles, industrial, agricultural, arid, polar, etc.). Measurements should be taken at 30 ground sites worldwide, with accuracy of ±0.25 percent for CO_2 , ±1 ppm for isotopes of CO_2, and ±0.25 ppm for O_2. Airborne measurements of CO_2 should be taken for the tropopause, with an accuracy of ±0.5 ppm, at 1 km resolution.

Resolution of these measurements would vary from 1 km in tropical, industrial, and agricultural regions to 5 km over the oceans and arid regions to 10 km over the ice sheets. The vertical resolution required would be 0.1 km throughout, with weekly sampling.

Priority: Pursue a consistent strategy for observations of O_3 from the ground to the lower stratosphere as a function of altitude, season, and characteristic region.

Required resolution of these measurements should be 0.5 km in industrial regions (weekly sampling); 1 km over agricultural regions (generally weekly but monthly during the winter); 1 km over tropical regions (weekly); 5 km over arid regions (monthly); 10 km over the ice sheets (monthly); and 50 km over the oceans (twice monthly). Vertical resolution required would be 1 km throughout. Accuracy of these measurements should be to ±5 percent and precision to ±2 percent.

Priority: Establish the distribution of H_2O and, through tracers that include the isotopes of water, the mechanisms that control the distribution of H_2O in the middle to upper troposphere as a function of altitude, season, and characteristic region. These observations should have a spatial resolution of 0.1 km, accuracy of ±5 percent, and precision of ±2 percent.

Horizontal grid scale should be 5 km in the tropics, 10 km in the subtropics, 50 km in the midlatitudes, and 100 km in the high latitudes. Vertical resolution should be 1 km in all regions, with weekly sampling.

Photochemical Oxidants Research Imperative

There are three types of pressing problems about the photochemistry of oxidants in the troposphere. The first is the problem of fundamental oxidation pathways. Critical unanswered questions concern the oxidation of organic compounds to stable products, the oxidation of reduced sulfur to sulfates that are central to acidity and to particle formation and growth, the oxidation of nitrogen compounds to nitrates, the direct oxidation of organisms and subsystems of organisms, and the oxidation of biomass. The second issue is the production of infrared active gases that control the Earth's climate. A significant component of this problem centers on ozone in the troposphere, but because of the coupling between chemical and dynamical time constants in this region, the problem involves other species, such as water in all its phases and isotopes, aerosols (the subject of the fourth research imperative immediately below), methane, and nitrous oxide. Still, a third problem is the control of oxidant export/import across international boundaries, that is, the coupling between regional and global scales. We address the three categories in order.

Oxidation Pathways in the Troposphere

Priority: Establish the sources, photochemical transformations, meteorological control, and deposition of trace oxidants (notably OH, NO_3, $O(^1D)$, Cl, O_3, Br) in various regions of the troposphere (e.g., boundary layer, continental regions, industrial regions, biomass-burning regions, western tropical Pacific, Arctic).

Priority: Analyze the sources, photochemical transformations, meteorology, and deposition of the chemical species that control the relationships among volatile organic compounds (VOCs), NO_x, and ozone in the major urban centers of the United States. Obtain simultaneous observations of the moderately long-lived species with a chemical lifetime between 1 hour and 1 year (NO, NO_2, O_3, CO, SO_2, H_2O_2, DMS [dimethyl sulfide], $HONO_2$, VOCs, peroxyacetylnitrate (PAN), and aerosols), short-lived species (OH, HO_2, NO_3, CH_3O_2), long-lived tracers (CH_3Br, CH_3CCl_3, CH_4, N_2O, CFCs), and meteorological variables (temperature, relative humidity, wind speed and direction), with required spatial and temporal coverage. Data on aerosol chemical composition are essential and must include particle carbon, particulate matter, sulfate, organic carbon, and elemental carbon. The requirements for spatial and temporal resolution will be specific to a given urban area because they are a sensitive function of topography and chemical composition, but diurnal data must be routinely secured as a function of altitude from the ground to above the boundary layer, with airborne platforms that are guided by real-time observations and the associated trajectory calculations defining air mass motion and residence times.

Production of Infrared Active Gases that Control Climate

Ozone is recognized to be an important component in the radiative balance of the Earth in the critical region of the tropopause.[14] It is also recognized to be increasing in the upper troposphere[15] and to be strongly linked to photochemical production via hydrogen and nitrogen radicals.[16] The upper troposphere is thus central to the link between the production of infrared gases and climate. From the perspective of scientific strategy, the upper troposphere is ideally suited for critical photochemical experiments because it provides an in situ laboratory with chemistry representative of the troposphere and yet is simple enough to reach closure on a range of experiments testing key hypotheses. There are several regions that should receive particular attention in the selection of trajectories. For example, the region that lies between Africa and Brazil, dominated by biomass-burning products, constitutes a profoundly different source region than the largely pristine region of the western tropical Pacific. The polluted continental regions and their wake regions in the Pacific rim are distinct from the Arctic upper troposphere. It has been clearly demonstrated that using the large dynamic range in species afforded by these regional differences, with the proper complement of tracers and careful real-time analysis of the meteorological fields, provides decisive causal links to be tested and established.

Priority: It is currently hypothesized (1) that ozone is catalytically produced in the upper troposphere via cycles involving radicals in the nitrogen and hydrogen families; (2) that NO_x is supplied by organic nitrates (PAN, etc.) and converted to nitric acid on roughly the overturning timescales of the upper troposphere; and (3) that HO_x is supplied by photolysis of relatively insoluble organic precursors such as acetone and methyl hydroperoxide. These hypotheses must be tested. Observations are therefore required of the short-lived and catalytically active radicals (OH, HO_2, CH_3O_2, $CH_3C(O)O_2$, NO, NO_2, and NO_3); the precursor species that may also be products (H_2O, acetone, CH_2O, CH_3OO_3, PAN, CH_4, and solar ultraviolet spectrally resolved); the product/reservoir species (HOOH, HONO, $HONO_2$, $HOONO_2$, N_2O_5); the sink species that are also local tracers

(CO, CO_2); the lower-tropospheric tracers (ethane, propane, biomass-derived CH_3Cl, C_2H_2, CO, CO_2, soot, pollution-derived C_2Cl_4, CFCs, lightning-derived NO_y, aircraft-derived CO_2, NO_y); and stratospheric tracers (N_2O, CO_2, NO_y, SF_6, CFCs, condensation nuclei).

These observations are required with a spatial resolution of 0.1 km in both vertical and horizontal dimensions, over trajectories that scan from sea level to the lower stratosphere. The observations must track specific air masses linking the source regions to the upper-tropospheric domain. This need demands supporting dynamical calculations that set the meteorological context and real-time analysis of the simultaneously obtained data to locate the boundaries of the air mass. This experimental strategy is Lagrangian but also contains an Eulerian component for vertical transections. Companion studies in the laboratory are a critical component of this research. A broad class of both homogeneous and heterogeneous molecular processes must be studied over the temperature range of 150 to 280 K in the 100- to 500-Torr pressure range.

Priority: These observations in the upper troposphere must be extended downward, first to include the midtroposphere and then to tie the analysis to the boundary layer. The observational array shares a great deal in common with that of the upper troposphere/lower stratosphere: observations of the short-lived and catalytically active radicals (OH, HO_2, CH_3O_2, $CH_3C(O)O_2$, NO, NO_2, and NO_3), the precursor species that may also be products (H_2O, acetone, CH_2O, CH_3OO_3, PAN, CH_4, and solar ultraviolet spectrally resolved), the product/reservoir species ($HOOH$, $HONO$, $HONO_2$, $HOONO_2$, N_2O_5), and the lower-tropospheric tracers (ethane, propane, biomass-CH_3Cl, C_2H_2, CO, CO_2, soot, pollution-C_2Cl_4, CFCs, lightning-NO_y, aircraft-CO_2, NO_y), stratospheric tracers (N_2O, CO_2, NO_y, SF_6, CFCs, condensation nuclei). These observations require a spatial resolution of 0.1 km in both the vertical and the horizontal dimensions, over trajectories that scan from sea level to the lower stratosphere.

Regional-Scale Links Across International Boundaries

International relations are increasingly entangled in disputes over the transfer of airborne pollutants across boundaries, transfers that initiate profound changes in oxidant, aerosol, acidic, and particulate deposition rates as a function of economic development, economic cycle, season, meteorological, and other conditions. These disputes are both acute and complex, involving the coupling of chemical, biological, and physical processes and demanding a high level of scientific proof under legislative or judicial scrutiny.

Priority: The high concentrations of ozone, sulfur, reactive nitrogen, VOCs, soot, PAN, and so forth are created both in focused urban regions and in more distributed regions (metro-agro-plexes) that depend sensitively on the particular blend of industrial activity, agricultural product, moisture level, temperature, and national and local infrastructure and priorities. The observational requirements are specific for the species and the trajectories, though the specifics may vary for specific national boundaries. The canonical suite of simultaneous in situ observations obtained with 0.1-km resolution is O_3, NO, NO_2, OH, VOCs, $HONO_2$, HO_2, CH_3OCH_3, PAN, DMS, SO_2, H_2SO_4, HCl, aerosol composition, number, size, and mass as a function of size, and tracers, specifying the region of origin of the air mass.

Aerosol Radiative Forcing and Climate Change Research Imperative

This imperative requires definition of the production and loss mechanisms, distribution, and optical properties of aerosols. Observations must be directed at processes that control aerosols from the fine scale to the global scale. Specifically, observations must clarify the following: (1) mechanisms controlling the rates of production of aerosols from those gases that are relevant to both direct and indirect forcing; (2) processes controlling the evolution of aerosols, including growth, activation to cloud drops, and wet and dry removal; (3) relations between aerosol optical depths and aerosol properties; (4) roles of specific chemical classes of aerosols, such as organics, in direct and indirect forcing; and (5) cloud-activating properties of different classes of ambient aerosols.

The character of scientific analysis in addressing the aerosol problem is critical to achieving progress because of the close but complex linking among chemical, biological, and physical processes. In particular, a critical strategy is to establish the relationship between key dependent variables (such as aerosol light scattering and absorption coefficients, number concentration of cloud condensation nuclei [CCN], etc.) and the major independent variables and then to test that functional dependence over a large dynamic range of variables. This strategy shares much in common with the approach of analyzing the structure of stratospheric ozone photochemistry, taking the form of the systematic analysis of *partial derivatives* linking dependent and independent variables. The explicit observation of these derivatives, or *response function*, provided the key evidence that overturned central tenets in ozone chemistry; it is the approach required in the field of aerosol chemistry.

This point is directly addressed in another report, *Aerosol Radiative Forcing and Climate Change,*[17] which casts the problem in terms of carefully designed "closure experiments"—experiments in which an overdetermined set of observations is obtained, and the measured value of a dependent variable is compared with the value calculated from measured values of the independent variables. This approach requires fundamental restructuring of both the observations and the architecture of the modeling effort. The key point is that, through a sequence of these analyses comparing calculated and observed variables and their associated derivatives, the fundamental mechanisms hypothesized to control the system can be tested.

Priority: Develop closure experiments with selected temporal and spatial resolution. For example, point measurements of aerosol number concentration and chemical composition as a function of particle size can be used to calculate simultaneously observed aerosol light scattering and absorption coefficients and the number concentration of CCN; and column measurements of the vertical profile of aerosol light scattering and absorption coefficients with simultaneously observed radiative fluxes that can be tested against measurements of aerosol optical thickness of the entire column and aerosol optical properties and with radiative fluxes at the top of the atmosphere.[18]

Priority: Pursuit of vertical column experiments that link nadir-viewing satellite observations of spectrally resolved absolute radiance with surfaced-based, column-integrated radiation measurements and in situ observations of aerosol chemical composition as a function of size, spectrally resolved upwelling and downwelling radiance (solar and infrared), light scattering (total and hemispheric backscatter), vertical distributions of aerosol backscattering, and meteorological/ state variables as a function of altitude.[19]

Priority: Development of the Lagrangian approach to testing closure between dependent and independent variables, where the observing platform moves with the volume element under analysis. Specifically, the evolution of aerosols in an air mass tagged with inert chemical tracers should be tracked with defined initial conditions, boundary conditions, and reaction rates, with the dependent variables being the time-dependent chemical and microphysical properties of the aerosol particles. Obtain simultaneous in situ observations of deviations of aerosol size, surface area, and chemical composition, SO_2, DMS (dimethyl sulfide), OCS (carbonyl sulfide), OH, $HONO_2$, H_2O, temperature, infrared and visible radiation field at 1 cm^{-1} resolution in selected trajectories that define the evolution of aerosols, from the source region to regions characterized by large and small aerosol optical depths, such as biomass burning, pristine, and industrial regions.

Priority: Obtain aerosol fields on a global basis from orbit, including the tropospheric distribution.

Priority: Map the size distribution, phase, and gas-phase environments of liquid/ solid particles in the upper troposphere and lower stratosphere, with simultaneous observations of SO_2, H_2SO_4, DMS, OCS, OH, $HONO_2$, NO_2, NO, H_2, temperature, and the radiation field, as a function of angle at 1 cm^{-1} resolution. These observations should be obtained in a Lagrangian reference frame.

Priority: Use multiplatform field campaigns that can effectively span the required dependent and independent variables in question, for example, the link between sources of anthropogenic SO_2 and sulfate aerosol or between organic aerosols and soot from biomass burning and radiative forcing—subjects also addressed by another NRC (1996) report. The oxidation rates and conversion efficiencies of SO_2 should also be observed. The necessary measurements include the following:

- SO_2 and H_2SO_4, nitrates, soot, organics, and trace metal concentrations.
- Photochemically active trace species concentrations.
- Short-timescale measurements of both sub- and supermicron nonsea salt sulfate and organics.
- Mass size distributions of aerosol chemical species.
- Number size distributions from 3 nm to 10 nm in diameter.
- Dynamic factors such as entrainment rates, turbulent transport to and from the surface, and mixing depths (see NRC, 1996).

Priority: Marine sulfur chemistry is directly tied to the formation of global-scale aerosol fields. These fields in turn are tied to both planetary albedo in the lower-troposphere boundary layer and the genesis of subvisible cirrus and visible cirrus, which are critical to the trapping of thermal infrared in the middle/upper troposphere. A nested set of hypotheses constitute the foundation of our understanding of marine sulfur chemistry:

- Climate is substantially affected by the radiation budget.
- The radiation budget is substantially influenced by atmospheric aerosols, both directly by scattering and indirectly by the influence of condensation nuclei on cloud radiative properties.
- Aerosols in the marine atmosphere are largely of natural origin.
- The source of natural marine aerosol is the oxidation of reduced sulfur species.
- DMS is the primary marine-reduced sulfur species.
- New particle formation occurs mainly in convective outflow regions above the marine boundary layer (MBL).
- DMS is oxidized in the marine atmosphere largely by OH, with a contribution from NO_3 in high NO_x environments.
- DMS oxidation leads to SO_2 with varying efficiency; SO_2 in turn is oxidized to H_2SO_4, which can homogeneously nucleate to form new particles.

While these tenets are plausible, they must be tested to establish the foundation of marine sulfur aerosol chemistry, its coupling to climate, and thus its link to human activity. Critical observations include the following:

- Direct spectrally resolved measurements of the flux divergence in the atmosphere, coupled with simultaneous aerosol and condensation nuclei measurements in clear air, cloudy air, and regions of cloud formation.
- Observations of new particle formation and identification of the major regions of new particle formation.
- Observations of reduced sulfur oxidation, including key intermediates and radical species, demonstrating quantitatively the coupling between DMS and aerosol precursors.
- Laboratory observations of the DMS oxidation mechanism, including direct observation of key radical intermediates under the conditions of temperature, pressure, and composition covering the range found in the marine atmosphere. In addition, continued developments in observational technology are critical to advancing the understanding of atmospheric chemistry (see Box 8.2).

BOX 8.2 Priority: Technological Developments

Developments in technology cut across the observational needs for atmospheric chemistry. Aircraft platforms are critical. Individual platforms or combinations of platforms must be capable of finding and following air masses over the timescale of the chemical processes under study (about one day). Lightweight fast-response instruments will be key components, as will fast data analysis to permit real-time decisions about flight trajectories. Observations of both radical and molecule species are essential to put limits on the rate of oxidation.

The following set of species, observed in outflow regions of convecting clouds (below and above the trade inversion) in a Lagrangian experiment would permit testing of the key hypotheses that DMS oxidation leads to new particle formation: OH, HO_2, NO, NO_2, DMS, DMSO, SO_2, H_2SO_4, $CH_3S(O_2)OH$, CH_4, CO, HOOH, O_3, H_2O, CH_3OOH, CH_2O, CH_3O_2, ultraviolet spectrum, aerosol size and composition as a function of size, Lagrangian tracers, and DMS eddy flux for MBL experiments.

Requirements:

- Develop parallel architectures for calculations that include aerosol size distributions in global-scale models.
- Develop lightweight sensors that significantly reduce the cost of deployment and enlarge the number of critical variables observed from a given platform.
- Develop small, rapid-response, low-cost satellites that attack specific scientific questions.
- Develop robotic techniques for obtaining data from ground-based, ocean-based, and airborne deployments.
- Develop instruments for in situ measurement of aerosol light absorption, angular scattering function, and asymmetry factor.
- Develop a compact, robust instrument to measure CCN spectra in a monitoring network or airborne mode.

Paleoclimate

Paleoclimate research over the past several decades has been essential in establishing the context of global changes observed during the course of the instrumental record. It has also pointed to the following research streams.

Research Imperatives

- *Global changes of the past*. Document how the global climate and the Earth's environment have changed in the past and determine the factors that caused the changes. Explore how this knowledge can be applied to understand future climate and environmental change.
- *Anthropogenic influences.* Document how the activities of humans have affected the global environment and climate and determine how these effects can be differentiated from natural variability. Describe what constitutes the natural environment prior to human intervention.
- *Limits of the global environment.* Explore the question of what the natural limits are of the global environment and determine how changes in the boundary conditions for this natural environment are manifested.
- *Climate forcing factors and controls.* Document the important forcing factors that are and will control climate change on societal timescales (season to century). Determine what the causes were of the rapid climate change events and rapid transitions in climate state.

Observational Implications

To pursue these research streams implies several directions for the observational efforts in paleoclimate research. Insights from such records as ice cores, coral bands, and tree rings have led to a number of principles related to observational stategy:

A global array of highly resolved continuous, precisely dated, multivariate paleoclimate records that sample the atmosphere, ocean, cryosphere, and land should be developed. For the identification of environmental change over the past two millennia, annual to decadal resolution will be required and for longer timescales decade-to-century-scale resolution. Continuously sampled and precisely dated records are essential. Tree ring and more recently ice core studies have set a standard of annually resolved dating that should be adhered to wherever possible. Multiproxy paleorecords should be developed wherever possible to maximize interpretations. The primary purpose of this global array should be to specify change over critical regions and during critical periods. For example, a major focus should include investigation of the frequency and extent of rapid climate change events (millennial to ENSO range) and to identify the controls on them.

Long paleodata series (centennial to millennial scale) should be complemented by spatial arrays of shorter records (decades) to enhance record interpretations and allow differentiation of local versus regional and wider environmental signals.

Integration and detailed calibration of paleodata and observational series will be essential. This approach will allow hindcasting of the relatively short timescale observational series. With coupled instrumental/paleodata series it will be possible to specify the frequency and magnitude of variability for major atmospheric circulation systems (eg., ENSO, North Atlantic Oscillation, North Pacific Oscillation) and extreme events (e.g., droughts, floods).

Paleoclimate and observational series should be coupled with process studies to specify controls on climate behavior. Ground-based and remote observing systems afford a unique tool for studying process. Such studies should be closely integrated with existing observational sites and regions from which valuable paleodata series may be collected. Future ground-based stations and satellite observations should be planned with paleodata in mind.

A clear demonstration of the "natural state of environmental variability" is needed as a baseline for assessing the influence of anthropogenic forcing on climate change. This will require the collection and interpretation of a broad array of paleodata series that capture variability in the physical, chemical, and biological boundary conditions down to regional and in some cases locally specific areas over several timescales.

Human Activities

Social, economic, and health observations are critical to global change research. Because human activities drive and are affected by global change, accurate observation (at different timescales) and understanding of these activities provide critical inputs to various fields of physical, chemical, and biological research on global change, as well as a basis for developing the end-to-end understanding of global change processes needed to inform policy decisions.

Current Uses of Observations of Human Activity

Observations of human activity are already in use in several fields of global change research. An important example is in research on the determinants and consequences of land use and land cover change. This has been designated a core research topic by the IGBP and the International Human Dimensions Programme on Global Environmental Change and was a NASA research initiative in 1998. Most land use research teams are using satellite data to provide biophysical measures of land cover. In addition, ground-based observations of human activity from a variety of sources are being linked to satellite data.[20] For example, district-level data from the Brazilian population and agricultural censuses are being used to model the causes of deforestation,[21] and combinations of individual-, household-, and village-level longitudinal data are being joined to biophysical data at the village level to study how deforestation in Northeast Thailand is linked to household-level human activities, including migration.[22] Each such research approach makes sense in the context of the region under examination and the substantive questions being addressed, but the diversity of social and economic data makes comparison and aggregation across regions difficult.

Data on agricultural inputs and management (e.g., tillage practices) are important to understanding such global change processes as carbon sequestration in soils. In the United States these data are reported at a county or state scale, so they cannot be reliably matched with spatially referenced soil and climate data in order to model the effects of agricultural practices on carbon sequestration or to examine the determinants of these agricultural practices. More spatially explicit data on the relevant human activities are collected in some European countries but are virtually nonexistent in developing countries.

Data on energy production and consumption have provided a critical input to the past decade of global change research. Detailed annual data on fossil fuel production for all of the countries of the world, developed primarily by the fossil fuel industries, are translated into carbon emissions based on measured and estimated values of energy content and carbon to energy ratios of each fuel. Uncertainty in global estimates of the total annual carbon emissions is estimated to be a few percent, while errors in year to year differences are much smaller.[23]

A similar key role is being played by data on the production of CFCs and nitrogen fertilizer and on nitrogen and sulfur oxide emissions in fossil fuel combustion. Many of the human source terms, however, are not well understood. Among these are carbon dioxide emissions associated with natural gas production, leakage rates of methane from the global natural gas production and distribution system, sources of methane arising from animal husbandry and rice cultivation, and sources of atmospheric nitrous oxide arising from managed ecosystems.

As the above examples and others in Chapter 7 indicate, efforts are increasing to link social, economic, and health data to biophysical data to improve understanding of the human dimensions of global change. However, a number of important observational issues must be addressed in the next decade. Some of these are similar to those in the biophysical sciences, and some are unique to human dimensions. This section focuses on those that are unique to human dimensions research, including the lack of involvement in USGCRP participation by key federal agencies, data comparability across political boundaries, georeferencing of social science data, and confidentiality issues that arise with human observations.

Observational Issues for the Next Decade

USGCRP Participation and Data on Human Activities

In the United States the lead federal agencies involved in collecting domestic social, economic, and health data are the Bureau of the Census, the Department of Education, the Labor Department, the Department of Agriculture, and various branches of the Department of Health and Human Services, such as the Centers for Disease Control and the National Institutes of Health. The U.S. Agency for International Development (USAID) has been the lead U.S. agency funding social data collection in many parts of the developing world. For all of these agencies their primary reasons for collecting social, economic, and health data do not involve issues central to global change research, nor did many of these agencies participate in the USGCRP during the first decade. This disconnect between those responsible for collecting (or funding the collection of) social, economic, and health data and those designing and maintaining global change observational facilities is present in many other countries around the world; the United States is not unique.

One result is that the vast majority of research on the human causes and consequences of global change has used social, economic, and health datasets that were not developed with global change scientific questions in mind. There are exceptions, of course, but the vast majority of scientists working on the human dimensions of global change have had to do the equivalent of repeatedly retrofitting remote sensors. There are numerous examples of scientific ingenuity involved in these efforts, and we anticipate this will continue. However, it is now time to take stock of the situation. Are the present social, economic, and health observational systems adequate for understanding the human dimensions of global change? What are the costs and benefits of bringing the federal agencies responsible for the bulk of the social, economic, and health data into the USGCRP? What human dimensions of global change research needs are not being met by current observational strategies? What is the potential for combining the collection of data on human activities and biophysical processes in the same settings, such as the NSF-funded Long-Term Ecological Research sites? In short, the time is ripe for an end to end review of the current situation and the observational needs for research on the human dimensions of global change.

Data Comparability Across Political Boundaries

Atmospheric and oceanic observational systems tend to impose a common data-gathering protocol across political boundaries, but for many reasons comparability issues often arise with social, economic, and health data. Perhaps the most obvious is language. With few exceptions, social, economic, and health data are obtained from human beings, using verbal or written communications to convey crucial concepts. As one moves from one language to another, some concepts become easier to convey and some more difficult. If a concept is difficult to convey in a given language, the quality of data collected in that language will be reduced. This is not a matter of poor translations, although that is sometimes an issue. Rather, it is embedded in the structure and nature of language. Since global research on human activities necessarily involves crossing language boundaries (which often overlap with political boundaries), additional effort is required to ensure comparability.

Social, economic, and health data are not collected by a global agency. Rather, they are collected by countries, organizations (such as hospitals or businesses), or by local nongovernmental agencies. To ensure comparability across collecting units, there must be coordination and a willingness on the part of everyone to cooperate. Frequently, local interests and the goal of comparability diverge. In the United States, for example, the collection of such basic demographic data as births and deaths is the responsibility of states, with the National Center for Health Statistics being responsible for coordination. For a variety of state-level reasons, there is variation across states in the collection of various items on birth and death certificates.

Comparability typically increases if one organization is paying for data collection and works to ensure comparability. The experience of the World Fertility Survey (WFS) is instructive. In the 1970s, when global population growth rates were substantially higher than they are today (resulting from substantial mortality declines but lagging fertility declines), an effort was launched to collect and analyze comparable data to further understanding of the determinants of fertility levels and variation. A total of 61 countries completed fertility surveys under the direction and coordination of the International Statistical Institute. The effort was the first attempt to collect global data on such an important issue using survey approaches. Funding for this effort came primarily from USAID, which restricted its use to developing countries. Low-fertility countries were expected to pay for their own surveys, and 20 low-fertility countries participated. The effort in developing countries produced datasets that were remarkably comparable, but comparability in developed countries was inadequate.[24]

The implications of the WFS experience need to be carefully considered in the context of global change research. It is now a given that better understanding is needed of the role of human agency in global change, and the word “global” needs to be emphasized. At present, relevant human dimensions data are being collected locally. Sometimes, local data are being used for local case studies; sometimes, local data are aggregated to the global scale, with various forms of imputation for those local areas not providing the relevant data. Both approaches can have problems, and it is time to systematically assess the strengths and weaknesses of the current situation.

Georeferencing Social, Economic, and Health Data

At its core, studying global change requires acknowledgment of the complexity of the global system and linking data across the various subsystems. Geographic information systems (GISs) have been providing an increasingly powerful tool for such linking.[25] Coordinate systems (e.g., longitude and latitude) provide a mechanism for linking across datasets, or GIS layers, that may have been collected at different times or with different observational techniques.

Historically, obtaining precise locational information has not been a high priority for those responsible for collecting social, economic, and health data. Typically, locational data have come under the purview of those responsible for the operational aspects of data collection. For example, census takers need addresses of dwelling units in order to conduct the census. By georeferencing social, economic, and health data, such human dimensions data could be more meaningfully linked to biophysical data. For example, modifying disease statistics (e.g., those supplied by the World Health Organization or the Centers for Disease Control) to include precise observations of spatial (e.g., longitude, latitude, altitude) and temporal (month and season) parameters for geotemporal referencing would allow integration of those observations with other observations of global change. The recent debate on the implications of global warming for the spread of infectious diseases would be resolved scientifically at a quicker pace if such spatial and temporal health data were already available.

Georeferencing social, economic, and health data would involve changes in the manner in which such data are collected and distributed. Some changes might be relatively minor. An example would be releasing the exact geographic boundaries for data that refer to an administrative unit, such as a district or subdistrict. Others will be more challenging, such as knowing the geographical locations where an individual's behavior might have an impact. The human dimensions research community is at a juncture where a careful assessment of georeferencing needs and capabilities is needed. Both costs and consequences need to be assessed. One possible consequence, breaching confidentiality, is addressed below.

Confidentiality Issues in Social, Economic, and Health Data

Data collection from humans often raises issues of confidentiality that may not arise with other global change observational systems. Sometimes confidentiality is protected by law. For example, information collected from specific individuals and households in the U.S. census cannot be publicly released until there is a reasonable expectation that most or all of those who participated in the census are dead. Thus, there is public access to the manuscript forms from the 1890 census but not the 1990 census. Alternatively, sometimes confidentiality is protected by an explicit or implicit agreement between those collecting the data and those providing the data. Either way, maintaining confidentiality is a characteristic of most social, economic, and health data systems, and without continued provision of confidentiality in human observational systems, the ability to collect human dimensions data would be severely compromised.

Confidentiality is maintained by a variety of mechanisms. One approach is to not make the data publicly available. Another is to strip away all identifying information, including georeferencing information. Yet another is to aggregate to levels sufficient to protect confidentiality beyond a reasonable doubt. Putting precise locational information into public use microdatasets would make it very easy for anyone to know the identity of specific individuals, households, or organizations. It would, in essence, provide a road map. Such activities by U.S. government data agencies would be unacceptable. Yet the scientific case for providing locational information so that human dimensions data can be linked to other global change observational systems is compelling. A careful review is needed to see if the confidentiality of individuals, households, and organizations can be protected while simultaneously advancing the scientific needs of the global research community.

Overview

The past decade has witnessed considerable scientific progress in understanding the human dimensions of global change (see Chapter 7). A major impediment to progress in understanding of the human causes and consequences of global change is the inadequacy of the observational base for the needed research. The time is now ripe for a systematic assessment of the role and needs for social, economic, and health data in global change research. Such an assessment should pay particular attention to issues of comparability, georeferencing, confidentiality, and relevance. Are current observational systems adequate and, if not, what is needed?

A MULTIPURPOSE, MULTIUSE OBSERVING SYSTEM FOR THE USGCRP: ELEMENTS OF SYSTEM DESIGN

Up to now, the observations taken for the six science areas have not been coordinated among themselves to form a single unified multiuse observing system. Nor has the path been clear from such a multiuse observing system to a permanent global monitoring system. Here, we describe the rationale and process by which an integrated multiuse observational system can be designed to serve the four science areas and explore the problems and opportunities involved in moving to the design and implementation of a permanent global observing system. We begin first with some overarching remarks that set additional constraints on or add information to the system design process.

Style of Observation

An observation can be taken for many different purposes. An exploratory observation is one taken in the spirit of exploration—no firm scientific rationale can be given for it because there are not enough data to make a scientific argument for a measurement. Such observations are very hard to come by (it is almost impossible for an investigator to propose such a measurement), yet all knowledge begins with exploratory measurements and every research program should include them. There are regions of the ocean that have never been measured, as well as parts of the upper atmosphere, and the land surface.

A critical measurement is one that tests a specific hypothesis. While common in particle physics, in which most accelerator experiments are specifically designed to test aspects of the current theory, these measurements are relatively rare in geophysics and even more rarely successful. Contradictory as it may seem, a program of observations can be hypothesis driven, even though a critical measurement may not exist.

A measurement can be made to document the secular change of some relevant climatic quantity, such as global surface temperature or upper-tropospheric humidity, for the purpose of documenting some aspect of global change and for providing the data to compare to models. Such a measurement could be critical if a prediction of such changes has been precise and unambiguous, but this rarely happens in geophysics because it is hardly possible to control the surroundings of a measurement.

Measurements can be taken as part of a forecast-analysis cycle, and these would generally be classified as an operational measurement. These measurements tend to be taken in a regular and systematic manner as input to an ongoing prediction system. While not performed (or funded) as research, such measurements can be extremely valuable since they make available to the research community observations that could (or would) not be supported through research—the upper-air observing network is a good example of this.

Some measurements are taken mainly to validate other measurements. Examples are measurements of SST from drifting buoys taken to calibrate the operational AVHRR satellite measurements of surface radiance. Because the satellite measurements are subject to cloud obscurations and are affected by aerosols in the atmosphere, which are not carefully measured, the in situ measurement of SST provides an absolute measure from which the satellites can derive global SST on a regular basis.

Some measurements are taken in a regular and systematic manner and, while serving the purpose for which they are taken, do not have the accuracy or reliability for some different purpose. An example is the upper-air network, which by itself has been incapable of documenting small temperature changes in the upper atmosphere. Increasing the accuracy or reliability of such measurements leaves them acceptable for their original purpose while making them useful for a different purpose.

Finally, there are proxy measurements of climate, usually from remnants of organic or inorganic materials stored in isolated natural formations, preserving records of past climates. Examples are deep-sea sediment cores, coral cores, ice cores, boreholes, and materials from old packrat middens. These kinds of records require great care in application to produce a record of physical quantities—a record that is often hard to interpret because the records (may) represent a single site but are invaluable because of the window they provide to the past.

Research Observations and Operational Observations

An operational system is one that is put in place to fulfill a specific societal purpose, generally requiring the regular and systematic delivery of a product in a specified cycle that has time constraints on its delivery. The purpose of the operational system may be the most commonly recognized one—weather prediction—or it may be for security (both civilian and military), resource discovery and management, disaster discovery and management (e.g., for fires and earthquakes), or various other commercial or societal purposes (the stock market ticker is a rapid operational measurement; the decennial census is a slow one). The measurement part of the system can be sited on a single platform or facility (e.g., a satellite), an aggregation of platforms (the upper-air rawinsonde network or the oceanic mooring array), or a complex combination of both.

A research measurement is usually designed to answer a specific scientific question and is usually finite in duration. What distinguishes an operational measurement from a research measurement is the absolute operational need to deliver a measurement regularly in a given time. This requirement has a number of consequences: there must be redundancy in the system in case a link or platform fails; there must be ongoing calibration, since the observation is to be used continually as part of a system and the consequences of incorrect information are serious; and there are changes in the system only as an improvement in response to the purpose for which it is taken. There can also be less emphasis on the longer-term absolute accuracy because forecasts may be based on relative accuracy or simply not require as great an accuracy of measurement as certain scientific measurements might demand. This tension or difference in purpose can be seen in the measurement program for weather forecasting versus the issue of detecting climate change.

Nature of an Observing System

An observing system consists of an architecture composed of various observational components and the interfaces connecting them. The design of the system reflects its purpose, the resources required to fulfill that purpose, and the resources available to implement the system. The design of the observing system is established by its users to maximize the system's utility in accomplishing the various purposes of its users. The system may be subject to various constraints, the most common being cost.

The purpose of the observing system may be unique, satisfying the needs of a single user or having the same purpose for a number of users. In the latter case (a single-purpose multiuser observing system), the design, implementation, and evaluation of the observing system proceed according to a common objective requiring cooperation among the users for funding and management but not requiring tradeoffs depending on differing objectives.

An observing system having multiple purposes is much more complex, generally requiring a cyclic design-implementation-evaluation procedure. This procedure only makes sense when the observing system is to be in place for long periods of time, so that a number of repetitions of the cycle can take place. The USGCRP has a set of scientific challenges; it has monitoring requirements with multiple-agency participation, and a research enterprise involving hundreds of university, government, and private-industry scientists—any observing system it puts into place is clearly a multipurpose, multiple-user observing system.

Design of an Observing System

The purpose of designing a system, rather than simply letting it grow haphazardly, is to optimize its utility among the users and minimize its cost—most likely some combination of the two. The complexity of the design increases as the objectives and number of users increase. Without such a design, it is likely that large amounts of money will be invested in taking observations, with no guarantee that the research objectives of the USGCRP are fulfilled or that the community of users feels satisfied in having their needs respected. The observing system needed to satisfy the stated aim of the USGCRP for monitoring is an even more difficult problem because the timescale of monitoring is effectively infinite: the monitoring system is to be considered a permanent observing system. To optimize the scientific utility of the observations needed by the many participants in the USGCRP, a rational process should be undertaken—the *system design* of a multiuser, multipurpose observing system.

A central aim in the design process is to achieve "maximum" scientific utility, subject to the inevitable constraints of funding, while being responsive to other demands for observations. The penalties for failing to design such a system are the loss of public trust; excessive costs and fragmentation of the observations that are taken; loss of vision of the scientific enterprise seeking to solve deeply interrelated problems; and, ultimately, scientific opportunities missed by the lack of cooperation among the different science areas. If there is one thing that a system design does ensure it is cooperation: every stage of a system design requires cooperation among scientists, engineers, and funding agencies.

The elements of a system design process are as follows:

1. *Determine the quantities needed based on the scientific research objectives of the USGCRP.* The quantities to be measured for the science areas of the USGCRP must be identified, and the accuracies to which they must be measured must be stated in terms of the scientific questions and objectives. A specific scientific rationale must be given for each measurement proposed, so that the scientific importance of the measurements can be recognized. All of the scientific users must be represented in this process and their needs evaluated on the basis of scientific priorities alone.
2. *Conduct a system engineering design study based on the scientific requirements of all users.* The possible instruments, platforms, strategies, and architectures for the system should be identified and the commonalties and conflicts among the users analyzed, using a consistent set of scientific criteria based on the scientific rationale presented by the users. The engineering design must take into account the possibilities of improved or lower-cost instruments and platforms over the lifetime of the observing system. The final design must ensure that the totality of the observations does indeed respond to the totality of the scientific needs.
3. *Develop an implementation process and priorities based on the engineering design and the practicalities imposed.* Once the engineering design is completed, the next step is beginning a consistent implementation process, consisting of the assignment and acceptance of responsibilities for the different parts of the system, a set of priorities by which the different parties can make implementation decisions, a set of incentives and disincentives for encouraging successful performance and punishing poor performance, and a management or coordination structure whereby the entire process is kept moving and decisions can be made. The implementation process is subject to practical constraints. Practicalities can be imposed externally (funding, infrastructure) or internally (lack of vision, aversion to cooperation), but only players not subject to internal constraints should be players in the implementation process.
4. *Appraise how well the implemented system meets scientific objectives in its actual performance.* A set of performance measures and evaluation criteria should be decided on in advance. Evaluation of the observing system must be carried out with reference to how the actual observing system as deployed meets the objectives of the science areas, subject to the practical constraints imposed on the system.

Changes should be considered in the implemented observing system reluctantly and only under well-defined circumstances. The reasons for changing a research observing system are that the original system is not meeting its design criteria, that newer and better technologies make some components obsolete, that scientific problems get solved to such an extent that the full suite of measurements originally proposed is no longer needed, or that new opportunities present themselves.

CASE STUDIES

Some perspective on the nature of multiuse observing systems can be gained by examination of the history of monitoring several crucial global change variables. While there have been some notable successes in long-term monitoring, such as the flask sampling network for CO_2 and other greenhouse gases, there are also examples of disappointing results in trying to obtain long-term consistent climate records. Two cases are examined here—that of the monitoring of solar output by satellite and that of recording cloudiness over the United States.

Solar Output

The ultimate source of energy for the entire climate system is the output of energy from the Sun. While the mean solar irradiance at the position of the Earth is about 1,367 W/m^2, the output of the Sun is variable over both long and short timescales. Much of the short-term variability is in the ultraviolet and is strongly absorbed by ozone in the stratosphere. This directly affects the temperature of the stratosphere, which in turn affects the rates of the chemical reactions that determine the concentration of ozone. Other parts of the spectrum are absorbed lower in the atmosphere by clouds, aerosols (both sulfate and carbonaceous), water vapor, and other minor constituents. Because the variability of these constituents affects the solar beam as it traverses the atmosphere, only by measuring the solar constant at the top of the atmosphere can the solar beam's true variability be known.

On longer timescales—say, over an 11-year sunspot cycle—the variability in the solar constant is on the order of 1 W/m^2. On still longer timescales, the variability in the solar constant can be as large as 4 to 5 W/m^2, as gauged by comparison to other Sun-like stars, which translates to less than 1 W/m^2 at the top of the atmosphere (irradiance must be multiplied by albedo and divided by four, since the area of the Earth is one-quarter the intercepted disc). The effect of such variability on the Earth's climate is not completely known, but if the sensitivity to radiative variations at the tropopause is 1.5 to 4.5 K for a 4 W/m^2 change (corresponding to a doubling of CO_2), variations on the order of a few tenths of a degree of global temperature can be forced by solar output variations on decadal timescales. Because globally averaged temperature is of this order, one cannot exclude the possibility that solar variability is the cause of decadal climate variations. Precise long-term measurement of the solar constant, accurate to 1 W/m^2 or less, is essential for testing this hypothesis. The case for accurate long-term measurements of the solar output is overwhelming and has been argued for by the

USGCRP and by every major international climate program. For example, an NRC panel[26] recently gave as its prime recommendation: "Monitor the total and spectral solar irradiance from an uninterrupted, overlapping series of spacecraft radiometers employing in-flight sensitivity tracking."

In commenting on this recommendation, the report provided the following illuminating discussion:

> This primary recommendation is particularly challenging and probably will not be achieved because of the dearth of access to space. A series of small spacecraft dedicated to solar monitoring could provide the necessary data. Overlapping observations are required to cross-calibrate measurements by different instruments whose inaccuracies typically exceed the true solar variability. Simultaneous observations from different instruments provide important validation that real variability, rather than instrumental degradation, is being measured and provide the redundancy needed to preserve the database in the case of instrument failure. Improved radiometric long-term precision and calibration accuracies would contribute to a more reliable solar forcing record. In lieu of spacecraft dedicated to solar monitoring, it may be possible to use NOAA or Defense Meteorlogical Satellite Program (DMSP) operational satellites, for which overlapping is a feature of the design.[27]

Figure 8.1 shows the current state of long-term measurements of the solar constant by satellite. Clearly, the measurement error between satellite instruments is far greater than what is needed. Commitments simply have not been made to the continuity and calibration of a series of measurements that scientists deem essential to understanding of long-term climate change.

Long-Term Variations and Changes of Clouds in the United States

Few elements of the atmosphere are more fundamental to understanding climate and its impacts on ecosystems and human systems than cloud amount and height. The specification of cloud cover is one of the most sensitive parameters in general circulation models, which are used to study climate. The legacy of measuring and reporting cloud frequency and height during the twentieth century is inconsistent with the importance of this fundamental element of the climate system.

Prior to the advent of commercial aviation, cloud amount was reported at least twice daily at several hundred NWS offices throughout the country. In these reports, observers were instructed to summarize the state of cloud amount during the night (sunrise observations) or the day (sunset observations). Most of the stations also had a sunshine switch that measured the amount of direct sunshine,[28] enabling scientists to detect any systematic biases between the two measurements. The advent of commercial aviation, however, required observers to ob-

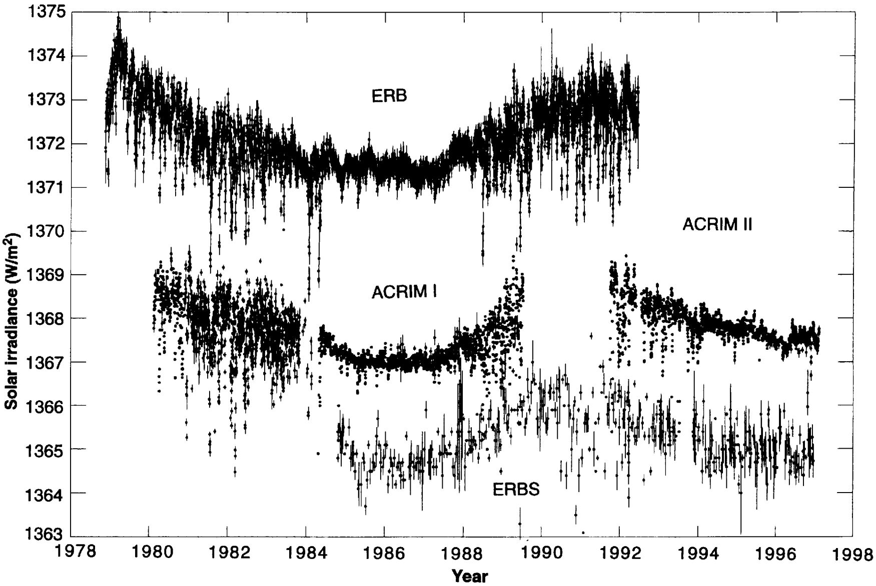

FIGURE 8.1 Total solar irradiance measurements, 1978 to 1996. Daily mean values and uncertainties shown for the Earth Radiation Budget (ERB), Earth Radiation Budget Satellite (ERBS), and Active Cavity Radiometer Irradiance Monitor (ACRIM) I and II experiments. SOURCE: Willson (1997). Courtesy of the American Association for the Advancement of Science.

serve cloud amount, type, and height of cloud bases each hour of the day. It is shown that during this transition more clouds were observed relative to the sunshine instrument,[29] suggesting that observers noted more clouds when they were required to search the skies each hour, compared with summarizing cloud amount during the previous 12 hours. Simultaneous with the hourly reports, the observers often moved from city offices to airport locations. At some locations a city office remained open, enabling cross-comparisons of cloud reports. During the time of rapid transition of stations to airport locations, a new sunshine recorder was introduced, with substantially different characteristics than the previous instrument,[30] thereby making it more difficult to quantify the effect of station relocations and changes in observing procedures.

At the outset of the USGCRP, another major change in cloud observing occurred. Automated lidar measurements were replacing human observers. These automated measurements were unable to detect clouds above 12,000 feet, which introduced a major discontinuity in the cloud observing network. A potential solution was to use geostationary satellites to detect clouds above 12,000 feet. Although methods were developed to identify broad categories of cloud amount—

such as clear, scattered, broken, and overcast—these categories were much broader than those typically reported by human observers. Moreover, the combination of automated lidar reports and geostationary satellite estimates indicated fewer overcast and more clear conditions compared with human observers. This result may have been overcome with appropriate transfer functions, but the cloud algorithm from the geostationary methods depended on an NWS "first guess" field of their operational model. A major change in this model produced still another bias in the record.

At this time, there is no suitable replacement for human observations of cloud amount at the several hundred sites across North America that had been reporting cloud amount and height for many decades. In response, the NWS has made an effort to continue both manual and automated cloud measurements at a selected number of stations for an indefinite period. Unfortunately, these cloud reports appear in a supplementary coded field message and are often missing.

Conclusions from Case Studies

As the above case studies demonstrate, there are a number of instances in which observing systems have faltered in delivering a consistent and calibrated record of global change. There are also some indications that many of the same problems may continue to appear in both ground-based and satellite observations relied on by virtually all of the science elements. For example, support for NOAA's Cooperative Observing Network, which is the basis for many of the longest surface temperature and precipitation records, continues to be a matter of concern. It also appears increasingly likely, based on current plans, that there will be a substantial gap between the end of the EOS PM-1 mission and the launch of the NPOESS. Such a gap would lead to data omissions and offsets in many of the data streams important for global change.

TOWARD A PERMANENT OBSERVING SYSTEM

Clearly, the USGCRP has the responsibility to observe, document, understand, and predict, to the extent possible, future changes in the global environment. The demonstration of, for example, secular trends in the Earth's climate requires analysis at the forefront of science and statistical analysis. Model predictions have been available for decades, but a clear demonstration of the validity of such predictions—a demonstration that would convince a reasonable critic on cross-examination—is not yet available. This lack is not in itself either a statement of failure or a significant surprise. It is, however, a measure of the intellectual depth of the problem and the need for carefully orchestrated long-term observations. The requirements for accuracy, continuity, calibration, in-flight standards, documentation, and technological innovation of long-term trend analysis are elsewhere described[31] and are endorsed by this report. See Box 8.3 for a summary of

BOX 8.3

Many of the observational issues raised in this chapter follow recommendations made over a number of years by other NRC reports. Below are some examples:

- *TOGA: A Review of Progress and Future Opportunities,* National Academy Press, 1990, 66 pp.

  "It is ironic and unfortunate that the new TOGA initiatives for long-term observations of the global atmosphere are being implemented in the face of an overall deterioration in some of the key elements of the World Weather Watch, whose long-term stability was taken for granted in the TOGA strategy document. . . . Some of the weather services are being forced to cut back on their contributions to the conventional observing system." (p. 55)

- *Opportunities in the Hydrological Sciences,* National Academy Press, 1991, 348 pp.

  "Improvements in the use of operational data require that special attention be given to the maintenance of continuous long-term data sets of established quality and reliability. Experience has shown that exciting scientific and social issues often lead to an erosion in the data collection programs that provide a basis for much of our understanding of hydrological systems and the document changes in regional and global environments." (p. 11)

- *A Decade of International Climate Research: The First Ten Years of the World Climate Research Program,* National Academy Press, 1992, 55 pp.

  "The WCRP has not been successful in convincing [others]. . . to halt the decay of conventional observing systems in the tropics." (p. 49)

  "Despite their importance, present capabilities for monitoring the climate system are deteriorating. . . Substantial effort by the WCRP. . . is required to. . . ensure baseline institutional and governmental commitment to the system." (p. 54)

- *Ocean-Atmosphere Observations Supporting Short-Term Climate Predictions.* National Academy Press, 1994, 51 pp.

  "When a set of observations begun under research funding is suggested for 'transition' to an operational agency, both the research and operational sponsors must be clear that the receiving agency has a commitment to sustain the observations, the technical capability to do so successfully, and avenues for the ongoing involvement of scientists." (p. 2)

continued

BOX 8.3 Continued

"Most satellite estimates will always require coincident direct-surface and upper-air measurements to perform the ongoing task of calibration, and surface platforms will be needed to make measurements not possible by remote sensing. The best determinations of the geophysical fields of interest will be obtained by combining satellite sensors with the direct observations of greater accuracy or more direct connections to the geophysical parameters of concern. Therefore, a well-chosen network of direct observations will become more, not less, important as satellite techniques advance." (p. 3)

- *Preserving Scientific Data on Our Physical Universe: A New Strategy for Archiving the Nation's Scientific Information Resources,* National Academy Press, 1995, 67 pp.

  "Observed data provide a baseline for determining rates of change and for computing the frequency of occurrence of unusual events. They specify the observed envelope of variability. The longer the record, the greater our confidence in the conclusions we draw from it." (p. 1)

- *Learning to Predict Climate Variations Associated with El Niño and the Southern Oscillation,* National Academy Press, 1996, 171 pp.

  "For future progress in the study of climate variations, it is essential to maintain what we already have, including the upper-air observing network, satellite altimetry, and the upper-ocean and surface-meteorological measurements made routinely in and over the ocean." (p. 137)

observational issues raised over a number of years in other NRC reports. While a complete discussion of observing selected variables is given in a collection of papers,[32] we extract 10 principles that have emerged to provide the guiding considerations that underlie the USGCRP's responsibility for observing, documenting, and understanding global climate change.

Principles of Long-Term Climate Monitoring

1. The effects on the climate record of changes in instruments, observing practices, observation locations, sampling rates, and so forth must be known prior to implementing the changes. This information can be ascertained through a period of overlapping measurements between old and new observing systems or sometimes by comparing the old and new observing systems with a reference standard. Site stability for in situ measurements, in terms of both physical location and changes in the nearby environment, should also be a key criterion in site selection. Thus, many synoptic network stations, primarily used in weather forecasting

but that provide valuable climate data, together with all dedicated climatological stations intended to be operational for extended periods, must be subject to such a policy.

2. The processing algorithms and changes in these algorithms must be well documented. Documentation of these changes should be carried along with the data throughout the data-archiving process.
3. Knowledge of instrument, station, and/or platform history is essential for data interpretation and use. Changes in instrument sampling time, local environmental conditions for in situ measurements, and any other factors pertinent to the interpretation of observations and measurements should be recorded as a mandatory part of the observing routine and archived with the original data.
4. In situ and other observations with a long uninterrupted record should be maintained. Every effort should be applied to protect the datasets that have provided long-term homogeneous observations. "Long term" with regard to space-based measurements is measured in decades, but for more conventional measurements long term may be a century or more. Each element of the observation system should develop a list of prioritized sites or observations based on their contribution to long-term monitoring.
5. Calibration, validation, and maintenance facilities are a critical requirement for long-term climatic datasets. Climate record homogeneity must be routinely assessed, and corrective action must become part of the archived record.
6. Wherever feasible, some level of "low technology" backup to "high-technology" observing systems should be developed to safeguard against unexpected operational failures.
7. Data-poor regions, those variables and regions that are sensitive to change, and key measurements with inadequate spatial and temporal resolution should be given the highest priority in the design and implementation of new climate observing systems.
8. Network designers and instrument engineers must be provided with long-term climate requirements at the outset of network design. This step is particularly important because most observing systems have been designed for purposes other than long-term climate monitoring. Instruments must have adequate accuracy, with biases small enough to document climate variations and changes.
9. Much of the development of new observational capabilities, as well as much of the evidence supporting the value of those observations, stems from research-oriented needs or programs. The lack of stable long-term commitment to these observations and the lack of a clear transition plan from research to operations are two frequent limitations in the development of adequate long-term monitoring capabilities. The difficulties of

securing a long-term commitment must be overcome if the climate observing system is to be improved in a timely manner with minimum interruption.

10. Data management systems that facilitate access, use, and interpretation are essential. Mechanisms that facilitate user access (directories, catalogs, browse capabilities, availability of metadata on station histories, algorithm accessibility and documentation, etc.) and quality control should guide data management. International cooperation is critical for successful management of data used to monitor long-term climate change and variability.

The remainder of this section concentrates on the transition from a research-focused observing system to a permanent operational component within the observing system of the USGCRP for global environmental monitoring. This transition is an essential objective for the next decade of the USGCRP.[a] Some of the considerations below are relevant to all observing systems, whether space based or in situ, and are independent of platform. However, there is a particular challenge—the transition from the NASA polar platform series to the NOAA NPOESS series—that raises certain unique challenges that must be recognized.

The Essential Transition: From Research to Long-Term Monitoring

A monitoring system is needed to detect secular change in the global environment. Even for research purposes alone, the system must be in place long enough to see a few cycles of the changes. For the dec-cen and biogeochemical components of the USGCRP, this implies an observational system with a very long lifetime. Moreover, from an operational point of view of tracking changes in the environmental state of our planet, a system is needed essentially for the duration of the perturbations and responses. Obviously, such a multipurpose monitoring system would fulfill important research needs; however, its cost is likely to be significant, particularly when integral costs are considered and not just annual costs. Therefore, it must satisfy operational purposes if it is to be sustained. An essential shift is needed within the federal government: the federal government must recognize that monitoring the changes in the global environment on significantly longer timescales than demanded by operational meteorology is in the forefront of the national interest.

For an observing system to be permanent, then, it must have some operational requirement. While in theory it is conceivable that some agency will adopt the rigors of accepting climate monitoring as an operational requirement, in

[a]The ENSO observing system, an oceanographic array for initializing predictions of aspects of ENSO, is undergoing this transition from research to operations now. The process is described in detail in NRC (1994b).

practice the monitoring of climate variability is not currently an operational requirement of the USGCRP nor is there an agency of the U.S. government that accepts climate monitoring as an operational requirement and is committed to it as a goal. The current designs for a global observing system by the GCOS and the Global Ocean Observing System[33] seem unattainable in practice because of the lack of such an operational mandate for any existing agency or the USGCRP.

The prospects for a permanent observing system therefore seem to rest on three possibilities:

- The USGCRP accepts environmental global change-focused monitoring as an operational necessity and makes the institutional changes needed to enforce the discipline that operational requirements demand.
- A new coordinating mechanism is created that has operational climate monitoring as a founding requirement.
- The permanent observing system is built using a quite different paradigm—that of coherence and evolution.

This paradigm sees individual components of the observing system growing out of research but being shifted into operations, each for its own purpose. As the system evolves, different parts of it may be operationalized for entirely different reasons. Thus, some parts of the ocean may be monitored for seasonal to interannual prediction, some for fish management, some for fish detection, some for pollution detection, and so on. The evolution process may take many years and only at some time in the future will it be appropriate to see what capabilities it has and what incremental measurements are needed to go from a congeries of individual measurements to an ocean observing system.

One of the difficulties in implementing the new paradigm is the necessity of converting research funding to operational funding. A research program can maintain a permanent observing system only when the system is relatively cheap and does not inhibit other research objectives. When there is an operational need for a system, funding must not come from research sources, else the building of a permanent observing system could gradually impoverish the research enterprise.

The paradigm still requires an institutional commitment to coordinate the various elements into the ultimate observing system, but it postpones the need for coordinated funding and thus allows (but does not guarantee) the coordination to evolve over the many years that would undoubtedly be required for this to occur. If we evolve the needed observational system as recommended, *a system design study still will be needed.*[b] There is a danger that without careful planning the system might contain a collection of instruments that do not together yield an adequate observing system to the scientific challenges, particularly those on the

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[b] See again the section on a multipurpose, multiuse observing system.

longer-term issues like ecosystems and climate from decades to centuries. A system design will give at least one measure of what is needed and, importantly, what is not.

A key issue that initializes both the system design and beginning the evolution process is the current and forthcoming satellite research missions: the EOS AM-1 and EOS PM-1 NASA polar platforms, the Advanced Earth Observing Satellite platforms from Japan, and the current ERS-1, ERS-2, and the future ENVISAT polar platforms from Europe as well as several more specialized research missions (e.g., TOPEX-Poseidon [Ocean Topography Experiment], TRMM, and the future Earth System Science Pathfinders). Another force on the process is the convergence discussions in which NOAA and the U.S. Department of Defense (DoD) (the Air Force) are converging the current Television and Infrared Observation Satellite (TIROS) and Defense Meteorological Satellite Program (DMSP) systems, respectively, in which they will go from a four platform system in sun-synchronous orbits (equatorial crossings at early morning, midmorning, and two in the afternoon) to a two-platform system (an early morning and an afternoon equatorial crossing). This is the planned NPOESS. Taking over the important midmorning slot will be the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) with its meteorological operational (METOP) polar platform.

There are several difficulties in going from the research missions to the operational missions.

- The current phasing of the EOS AM-1 and EOS PM-1 and the NPOESS schedule produces a potentially significant observational gap. This gap is currently increasing because of the longevity and reliability of the current assets (e.g., the TIROS and DMSP systems on orbit and in construction). What is to be done to appropriately fill the gap is not clear.
- The linkage between EOS AM-1 and the METOP midmorning platform of EUMETSAT is even murkier than that between NASA and the U.S. operational satellite agencies (NOAA and DOD).

It is crucial for global change research and monitoring that future operational satellites should, to the extent practical, have the qualities necessary for global change science identified in this report. To resolve these difficulties and move onto a course that is sustainable and meets the long-term observational challenge posed by global change will require political courage and strong and continued leadership by all parties. It will not be easy; it is, however, essential.

NOTES

1. Karl et al. (1995a).
2. Sellers et al. (1997), Fung et al. (1987), Myneni et al. (1997), Potter et al. (1993), Randerson et al. (1997), Braswell et al. (1997).
3. Braswell et al. (1997), Myneni et al. (1997).
4. Skole and Tucker (1993).
5. Wessman et al. (1998).
6. Martin and Aber (1997).
7. Aber and Federer (1991).
8. Vitousek et al. (1997), Braswell et al. (1997).
9. Wahl et al. (1995).
10. Kanciruk (1997).
11. Vörösmarty et al. (1996).
12. Rasmussen and Carpenter (1982).
13. E.g., Holton et al. (1995).
14. See Intergovernmental Panel on Climate Change (1995).
15. See Logan (1994).
16. See Wennberg et al. (1998).
17. National Research Council (1996).
18. Ibid.
19. Ibid., Russell et al. (1994).
20. National Research Council (1998b).
21. Wood and Skole (1998).
22. Entwistle et al. (1998).
23. Marland and Boden (1997).
24. Cleland and Scott (1987).
25. National Research Council (1997).
26. National Research Council (1994a).
27. Ibid.
28. Karl and Steurer (1990).
29. Ibid.
30. Quinlan (1985).
31. Karl et al. (1995a).
32. Karl et al. (1995b).
33. Ibid.

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9

Processing and Distributing Earth Observations and Information

INTRODUCTION

All scientific endeavors based on observations, including those envisioned for the U.S. Global Change Research Program (USGCRP), must acquire relevant and accurate data, transform the data into scientifically useful information, and distribute the information to scientists and others who will use it to advance understanding, applications, or education. Data operations for the USGCRP and the National Aeronautic and Space Administration's (NASA) Mission to Planet Earth are particularly challenging. First, the Earth Observing System (EOS) and the spacecraft of other nations will produce an unprecedented variety and amount of data. Second, the integration of data from other agencies and sources, including operational and in situ observations, will be necessary for a wide range of scientific purposes. Finally, the higher-level and summary data products will be sought and used by a broad constituency through global electronic networks.

THE EOS DATA AND INFORMATION SYSTEM: IMPLICATIONS FOR THE USGCRP

This chapter concentrates on the data and information issues associated with EOS: they are urgent in themselves, and they are also a prologue for the issues that must be resolved for the USGCRP as it develops early in the twenty-first century.

From the beginning, the space observation and data-handling components of EOS were considered to be essentially independent of one another. The instruments are to acquire the data, and the data are then to be processed and distributed by the EOS Data and Information System (EOSDIS). However, a number of significant issues, discussed in the sections below and covered in greater depth in Annex 1 (which provides a short history of the EOSDIS), have swirled around EOSDIS from the beginning.

Attention over the past decade has focused on the design and implementation of a data and information system—with emphasis on the "system." Today, in view of the issues, it may be advantageous to focus less on a system and more on the capabilities and attributes that will enable and encourage the most effective use of the data by scientists and others.

Issues and Tensions

The motivation for public investment in EOS is the enhancement in scientific understanding, applications, and education that will result from the observations. But for these benefits to be realized, the data must be readily available to all who would use them. Over the past decade the advance of computer and information systems has dramatically altered the possibilities of taking advantage of data streams with large data rates. Nevertheless, many issues remain. In fact, many of these issues are true for any large data system and hence also bear on the so-called Global Change Data and Information System. The only issue unique to EOS is the fact that it is space borne with specific instruments. There are three different areas of concern:

- *Data stream processing and operations.* For Earth observations such as those of EOS, there will be strong interdependencies among instruments that must be resolved during data processing, and thus algorithmic complexities and sequencing issues complicate the problems associated with large data rates. The instrument teams must find ways to interact effectively to produce accurate data and to document carefully and rigorously what has been done to the observations. These are management not technology issues, and it is important to seek a solution that is no more complex than the particular circumstances require.
- *Archiving.* Technological and conceptual advances together have dramatically improved communication lines between the sources and potential users of data. Individual scientists can have capabilities at their workstations that rival those of computer centers of a few years ago; and the power of contemporary communications capabilities such as the World Wide Web, which have revolutionized interactions among scientists as well as access to data sources. How much we should depend on this rapidly evolving environment in developing EOS data capabilities has been controversial. Questions about how to store and eventually archive data are also pressing, with modern technologies obviating old assumptions and offering wide replication of datasets as a potentially more secure approach than formal archiving.

- *Decisions on priorities.* Developing any data management capability generates questions about what needs to be done and how do it. Clearly, the data and information capabilities associated with EOS should be responsive to the needs of science and its applications and should stimulate continuing advance. Most scientists will not want to be concerned with operations of the data system, but they know that decisions about data processing, access, and archiving will affect the quality and quantity of their work. The most important information system issues concern control, participation, and responsibility. As in managing any scientific program, these issues include setting priorities among known tasks, openness to new opportunities, and accountability for the use of public funds, all while facilitating the work of users. The broader the user community and the more complex the system becomes, the more likely it is that competing demands and conflicting requirements will lead to chaos rather than consensus.

It has been assumed for a decade or more that the processes of producing, using, and archiving EOS observations could be described by a set of requirements specifying data rates and paths, specific capabilities and facilities needed by users, interoperability mandates, and archiving methods. The presumption has been that such a collection of requirements would lead, through the system design process, to a system that would resolve the issues discussed above.

Today, we understand that this approach often leads to failure in creating large information systems, as has been demonstrated by a number of well-publicized efforts at the federal and other levels. The failures become inevitable because user needs are not well understood, are difficult to describe quantitatively, and lead to serious conflicts. Moreover, user needs will inevitably evolve rapidly as soon as users begin to work with the data. Hence, a system constructed on the basis of requirements derived from stated user needs has little resiliency, in part because the requirements often reflect an implicitly specified architecture. The problem is exacerbated by the federal procurement process, which often specifies a fairly detailed architecture along with a plethora of "requirements."[a] Under such conditions there is little room for innovation, and the probabilities of failure and extraordinary cost, as has been amply demonstrated, are high.

The astounding growth, first, of the Internet and, second, of the World Wide Web, illustrates another development path. In both cases a relatively simple set of rules or interface standards specifies how interactions will proceed. Users, through the creative power unleashed by highly distributed but interactive efforts, have developed the rest using the capability provided by the standards.

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[a] The Request for Proposals issued by NASA for the EOSDIS core system in 1991 specified the architecture of the system and listed more than 1,000 specific requirements for it to meet.

The long-standing tension and controversy over the basic nature of the EOS information system thus lead to a number of questions: Do contemporary information system concepts and technology suggest entirely new models? What actions will increase the probability of success of the information system and the activities it supports? Should the responsibilities of the scientific and other user communities be different than in the past? Should the responsibilities of NASA and other components of the federal government be different than in the past? Finding appropriate answers to these questions is critical to the future of the USGCRP and, in fact, to the future of all Earth observations. Again, we note that these issues are not unique to NASA or EOSDIS.

The Original EOSDIS Federation Proposal

The National Research Council (NRC) committee authoring the present report—the Committee on Global Change Research—examined NASA's plans for EOSDIS as part of its 1995 review of the USGCRP and made recommendations for significant changes in direction.[1] The committee observed that the long-term functional requirements for EOS and other Earth information systems remain valid and must serve as the criteria for design and for judging success. It concluded that any concept for an EOS information system should ensure that several goals are met:

- Users can readily locate datasets with real and valuable scientific content.
- Users can access and utilize such datasets readily and in a timely fashion.
- Collaborative analysis and research are stimulated and encouraged.
- Demonstrable progress in scientific endeavors and applications to other activities is evident.
- Scientists and scientific teams can use the system for interaction as well as a form of electronic publication and dissemination of results.

At that time the committee argued that the commitment to the "right model" for governance, management, and operation of the system would ensure that "the details related to design and technology would readily fall into place."[b] Arguing that expectations for the information system mandated that the scientific community accept full partnership and shared responsibility, the committee identified two key requirements for the system model: that it use an open management approach in which consequential decisions are made with community leadership and with assignment of responsibilities based on peer review, and that it encour-

[b] Note that this view of the model or conceptual framework for information system governance and management is quite different from the process described earlier, in which the implicit assumption is that a "right system" can be designed.

age innovation and creativity through wide participation of the scientific, public, and private sectors, and the committee then recommended that:

> *Responsibility for product generation and publication and for user services should be transferred to a federation of partners selected through a competitive process and open to all.*[2]

In this context a federation entails an association of autonomous partners creating a central structure to provide leadership and administration and agreeing to abide by certain interface standards, business practices, and expectations of conduct to achieve a common purpose (further basic information about this arrangement is presented in Annex 2, on an EOS information federation). To assist in implementing the recommendation, the 1995 report suggested that NASA explore key issues with a number of prototype efforts.

The 1995 recommendations generated considerable discussion and examination of alternatives, especially by NASA advisory committees involved with the EOS project. As this discussion evolved, the differences between the original EOSDIS model and various federation models became clearer. The original concept might be described as a "data push" model, in which the flow of data from instruments would be processed in data centers and converted into a hierarchy of predetermined data products that would be available to users through a request mechanism. The federation concept retains "data push" processing of instrument data into physical variables but then expects "data demand and pull" to shape the higher-level products in response to actual needs, including data for scientific studies sponsored by the government, information summaries for business and policy considerations, and a wide range of purposes developed in a valued-added market.

A panel of the NRC Committee of Geophysical and Environmental Data held a workshop on "federated" structure (i.e., the federation of partners recommended in the NRC 1995a report) for the Earth Science Enterprise (ESE). The report examines federated structures from a variety of organizations—libraries, international organizations, industry, government, and academia—and discussed objectives, governance, potential costs and benefits, measures of success, and lessons for an ESE federation.[3]

Revisiting EOS Information Federation Models

The EOS information federation model recommended by the NRC in 1995 envisioned that NASA would convert the EOS data it received from the spacecraft into geophysical units and would couple this information with spatial and temporal coordinates to produce a basic data stream. Further processing, distribution, analysis, and combination of the data would occur in two distinct efforts. The first would involve various federation partners supported by NASA through a competitive peer review process; the second would involve federation partners

TABLE 9.1 Three Possible Models for the EOS Information System

Model	Original EOSDIS Model	A New Federation Model	A Free Enterprise Model
Description	EOS instrument data processed by NASA, with algorithms developed by instrument teams.	Instrument teams produce basic data streams with federal support and make them available to all others.	All NASA and EOSDIS data funds flow to grants for research or applications to buy data, thus creating a market and a distributed capability.
	Defined datasets and products prepared and distributed to all users by NASA or its contractors.	All further data processing done by federation members, some with NASA support to ensure a representative menu of EOS products.	
	Government archives basic data and datasets.	Government archives basic datasets.	
Main advantages	Data streams under NASA control; a specified set of products can be expected with confidence.	Principal investigators responsible for initial processing; innovation likely in development of EOS products and information management capabilities; federation engages scientific and other communities.	Market-driven approach should respond well to highest-priority efforts in science and applications; multiple capabilities and pathways will develop.
Main disadvantages	Lack of flexibility and innovation; conflicting requirements and high costs likely.	Federal support not available for all potentially useful products; market may be thin for important products.	Some data will never be processed unless NASA manipulates market with research grants.
Comments	System subject to unilateral NASA control.	Appears desirable for global change researchers, but some science areas may be neglected.	Both archiving and international collaboration present serious issues.

or others who developed value-added products at their own expense and made their own arrangements for distributing them to customers.

A wider range of models for an EOS information system have been explored. Table 9.1 describes and examines three such models, including the original EOSDIS, a free enterprise model, and a combination of the two, denoted as a New Federation Model.

In the NRC 1995 federation model the functions of the original EOS model would be performed by federation partners under contracts secured through a competitive process. Thus, the government would be responsible for determining a set of products to be produced under contract. That model was thus intermediate between the original EOS model and the particular new federation model described in Table 9.1, which allows more innovation in the federation but provides less assurance that a specific set of products will be available.

The new federation model described in Table 9.1 provides a new approach to space-based observations for global change and other Earth system research. At the present time, as typified by EOS, the federal government contracts for the construction of an instrument to fly in space and for algorithms to process data from the instrument on a government computer for subsequent distribution to other scientists. In the new federation model the government would contract for delivery of a stream of data in geophysical units, along with navigation and other descriptive information, to a network that would make it available for further processing. Thus, rather than the data being processed on a government computer with algorithms provided by the instrument team, the data would be processed directly by the instrument team on its own computers or by a contractor under the team's control.

Except for this change in responsibility for basic data processing, the new federation model is similar to the EOS model until the basic data processing is complete. Then it becomes similar to the NRC 1995 federation and, in some respects, to the free market model. A significant advantage is thus that the basic data processing is performed by the principal investigators under government sponsorship and management through the contract, presumably ensuring that the data streams from space will indeed be made available to both science and applications in a timely manner. Another advantage of the new federation model is that it provides a mechanism for NASA to continue to support experimentation and innovation in information access, management concepts, and technology that will advance global change research and applications, thus enhancing the value of the EOS data.

MOVING TOWARD A NEW EOS INFORMATION SYSTEM

With the EOS it has been recognized from the very first that making the data available for scientific research and other applications is as important as acquiring the basic observations from space. Indeed, if the data do not serve public purposes of enhancing, understanding, and supporting other important activities, then there is no point in building the instruments and no point in launching and operating the spacecraft that carry them. Thus, NASA faces the dilemma that it must create a data system in the public interest but that it cannot create a satisfactory system by itself.

A number of critical issues will arise for any choice of model for an Earth information system:

- The community must decide what it really wants and what responsibilities it is willing to accept. NASA and other senior federal officials must think through their attitudes about a federation or partnership, including what elements will be funded and how incentives are to be created and made effective.
- NASA must manage a complex relationship between itself and the parts of the EOS and global change research community that it is funding; it must provide incentives so that the associated institutions perform for the benefit of the entire community.
- The government must adopt some model and then be prepared to implement it.

Many members of the EOS community have been thinking about EOSDIS for years and about federated models at least since this committee's endorsement in 1995.[4] A wide range of models has been considered, as shown by Table 9.1. The committee believes that the new federated model offers advantages over its 1995 proposal and that:

The new EOS Federated Information System, including processing by the instrument teams to create the basic geophysical data, should be thoroughly explored to be sure it meets the needs of the four segments of the community: data producers; scientific assimilators and data consumers, including global change scientists; other scientific users; and the private sector. The new model should then either be adopted for EOS and the USGCRP or modified appropriately.

Federations seem to be successful if their defining architecture concentrates on the highest-level goals and the interfaces between components. For the EOS Federated Information System the implication is that at first we try to envision only the capabilities that will facilitate scientific progress, the basic structure of the federation, and perhaps the inviolable rules. A candidate set of such rules is the following:

- The low-level data from all EOS sensors (the telemetry from space) must be preserved for at least several decades in a manner that enables access to, and reprocessing of, the entire dataset.

- All data products from EOS sensors, including calibration and validation information, must be readily accessible and available to any user or entity that wishes to provide a new service.
- Access interfaces to the EOS Federated Information System should be clearly defined and sufficiently open to allow a broad range of services to be developed now and in the future.
- No data, product, or service produced from EOS sensors shall be restricted to any user based on proprietary rights.
- Data and service providers shall be able to charge for their services, as allowed by the federation.

The formation of such a federation will require initiative and action on the part of the science community and the private sector. The governance structure must provide an adequate legal status for financial operations and an adequate executive structure to maintain operations and ensure that the federation is fulfilling its purpose. Presumably there will be both a formal structure with a governing board representing substantial partners and a wide range of volunteer activities.

For such an organization to be successful, the incentives, as perceived by the participants, must be aligned with the purpose of the federation. Thus, NASA, as the principal initial source of funding, must devise contract award and management procedures that attract federation partners committed to high-quality science and service to their community. Mechanisms will be needed to ensure institutional credit for the complex task of publishing reliable and trustworthy datasets and supporting users, as well as for the usual regard for well-founded scientific conclusions (see Annex 3, on producing trustworthy scientific information in the EOS Information Federation).

The federation must also resolve the apparent conflict between charges restricted to the costs of filling user requests (COFUR) and the aim of stimulating for-profit and not-for-profit organizations to develop value-added products. One possibility is to allow amortization of the costs of developing and producing value-added products to be charged to all users, with profit restricted by agreement or obtained only from for-profit use of the product. Another is to apply COFUR rules only to researchers seeking data for projects directly supported by federal funds and to allow the market to shape the pricing structure for all other public and private purposes. A third is to apply the COFUR policy only to those products that were produced entirely with government funding. Regardless of the specific model, the federation concept includes an assumption that funds to acquire EOS data, whether for basic products or value-added datasets, will be made available in federal research grants, thus creating part of the market for EOS data and supporting the federation.

The relatively intense discussion of the 1995a NRC recommendation—namely that NASA adopt a federated competitive approach to EOSDIS—has sharpened understanding of the advantages and disadvantages of a range of data and information system models. It has also intensified awareness of two unavoidable conclusions: NASA is accountable for what happens to EOS data, no matter what information system is implemented, and the scientific community can recommend a structure and an approach but cannot decide what to do.

For the future we envision a federation that will be effective in transcending lists of requirements by providing enabling capabilities and by focusing on the value of EOS data for science and applications rather than on system mechanics. The operational details of the EOS information system will then fade into the background of an existing supportive, but largely invisible, global information infrastructure, and scientists will be able to concentrate on science.

NOTES

1. NRC (1995a).
2. Ibid.
3. NRC (1998).
4. NRC (1995a).

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10

Modeling

INTRODUCTION

The possibility of major changes in the global environment due to human influences presents a difficult challenge to the scientific research community: to relate causes and effects and to project the course of change on a global scale and for many decades. Approaches based purely on observations are inadequate for prediction. Such rapid externally forced changes have no precedent. Moreover, the response times of many parts of the Earth system are slow, and there is a great deal of variability from place to place. Scattered observations over short time periods are unlikely to reveal clear and useful trends. Furthermore, many important processes—such as those that occur in the soil and in the interior of the ocean—cannot be measured directly or adequately over large areas. We therefore need models—numerical representations of the Earth system—to express our understanding of the many components of the system, how they interact, how they respond to perturbations, and how they feed back to provide dynamical controls on overall system behavior. It is thus evident that the study of global environmental changes—their causes, their impacts, and strategies for mitigation—inescapably requires models that encompass the mutual interactions of the principal components of the Earth system.

There is, however, a fundamental difficulty in that many environmental issues require prediction on relatively long timescales and require integration over large spatial scales. Extrapolations from models over such long time spans are prone to error as small discrepancies from reality compound; moreover, there remain open and complex issues regarding downscaling. Hence, research-quality observational datasets that span significant temporal and spatial scales are needed so that models can be refined, validated, or perhaps rejected. Such data must be adequate in temporal and spatial coverage, in parameters measured, and in precision to permit meaningful validation or rejection of models. It is equally important that models be designed to permit confrontation with the real world through observations and that they be tested sufficiently and explored, including creating ensemble runs under differing conditions.

Over the past decade there has been remarkable progress in modeling, not only in simulating the principal individual subsystems but also in treating key linkages such as those between the ocean and atmosphere. This record of progress within the U.S. Global Change Research Program (USGCRP) makes it reasonable to expect that within the next 10 years of the USGCRP the scientific community will develop fully coupled dynamical (prognostic) models of the full Earth system (see Figure 10.1[1]) that can be used on multidecadal timescales and at spatial scales relevant to important policy formulation and impact assessment. Such models exist in rudimentary form today. Future models will advance in completeness, sophistication, and proven predictive capability. The key will be to demonstrate some degree of prognostic skill in these future coupled models of the Earth system.

This development process will not be isolated from the needs of policy and decision making. Some of these Earth system models will be integrated into more encompassing models that link human and nonhuman processes or will be employed in various analytical or deliberative processes to inform decisions. Providing useful insights to inform decision making on global change will require dynamic representations of complex possible cause-effect-cause patterns linking human and nonhuman components of the Earth system. To develop and validate such models, observations of the Earth system must include data on human impacts from, and contributions and responses to, global change. At present, human influences generally are treated only through emission scenarios that provide external forcings to the Earth system. In future comprehensive models, human activities will interact with the dynamics of physical, chemical, and biological subsystems through a diverse set of contributing activities, impacts, feedbacks, and responses.

The focus of this chapter is on the path for realizing and evaluating a suite of such Earth system models. It should be recognized at the outset that the multidecadal timescale places important constraints and demands on the character of such models. The most important constraint is that models must confront the ever-expanding (though still inadequate) set of time series data, both in situ and remote. The canonical example of the extraordinary value of time series information is the Keeling Record, the daily measured atmospheric concentration of carbon dioxide from Mauna Loa (see Figure 2.10 in Chapter 2).[a] The importance

[a] It is worthwhile to note that obtaining this unique record was threatened more than once by budget cuts and shortsighted federal managers.

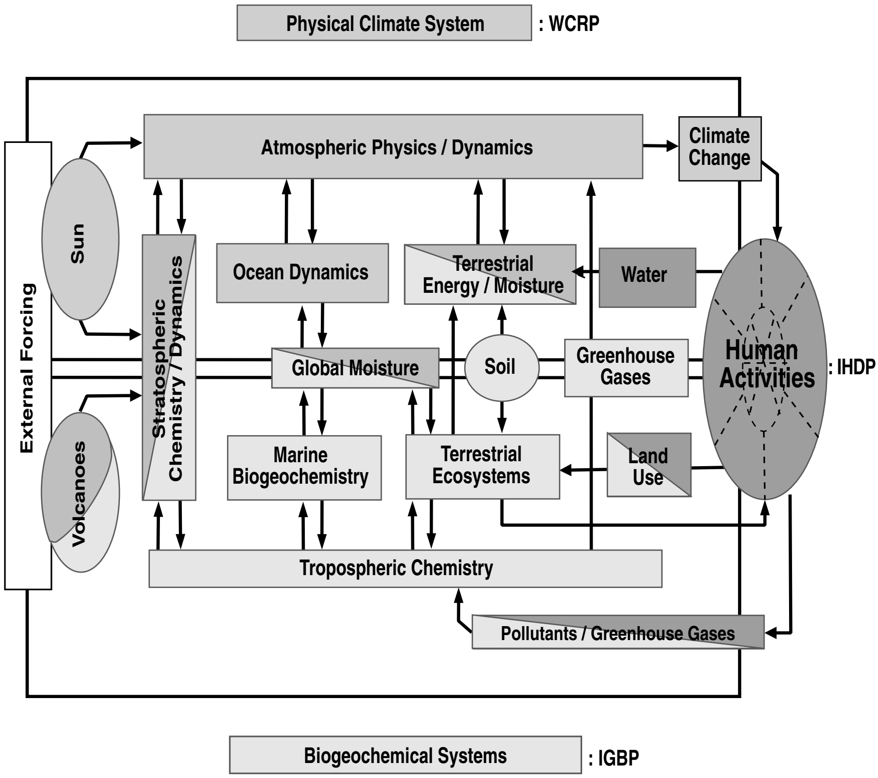

FIGURE 10.1 Conceptual model of the Earth system. SOURCE: Adapted from NASA (1986).

of this record flows from several aspects: (a) its scientific quality in terms of accuracy and precision, (b) its temporal quality in terms of resolution and duration, (c) the importance of the parameter measured (atmospheric CO_2), and (d) the site (remote and well positioned for a global measure). The Keeling Record set a standard that subsequent measurements have sought to emulate. Moreover, it demonstrates the value of measurements taken to determine the state of a system rather than to test a specific hypothesis.[b]

The long temporal scale also demands inclusion of the biosphere and other coupling across critical interfaces. Over timescales of decades and more, the biosphere may be expected to respond dynamically to changes in many compo-

[b] This report emphasizes the latter, but the importance of the former must not be overlooked. See Chapter 8.

nents of the Earth system. More broadly, if we are to understand both the function of living ecosystems and their effects on the environment, we must have a better grasp of the controls and distribution of biological activity in the context of the overall Earth system, including the actions of humans. While necessary, observations will hardly be sufficient to understand the present and to predict the future role of ecosystems in this global context. Consequently, in this context, developing more realistic models that include successional dynamics and migration patterns of vegetation will be increasingly important in the coming decade. In sum, interactions among components over these longer timescales are likely to be as important as processes within each. Models must therefore deal with interactions between terrestrial ecosystems and the atmosphere, physical and dynamic interactions between the ocean and the atmosphere, the chemistry and physics of the atmosphere and ocean themselves, the land-ocean interface, and even the challenge of incorporating the human component. Each of these heterogeneous components and each of the diverse interfaces between them pose particular demands on research and model development.

Models of the fluid subsystems, the atmosphere and the ocean, have been developed almost in parallel with the advance of computational capacity. On the other hand, models of the terrestrial and marine biosphere have been paced by a shortage of observations at adequate time- and space scales and by the slow development of a new community of scholars willing to confront the biological system at large spatial scales. Modeling the role of humans in the Earth system has been controversial from the outset. Computational consideration of the global role of humans dates back, in part, to the provocative early system dynamics studies sponsored by the Club of Rome.[3] These models were criticized for their simplistic assumptions about complex human behavior; their inadequate treatment of market forces; and their lack of explicit treatment of physical, chemical, and biological processes. However, they did awaken many to the possibility for quantitative simulation of complex systems beyond econometrics, and they contributed toward convincing the policy community of the importance of taking a system view, including explicit consideration of feedback loops and environmental constraints.

Looking more closely, we find that computer-based atmospheric models were first developed in the 1940s for weather forecasting—that is, to predict the near-term physical behavior of the atmosphere. In the subsequent development, there has been a natural branching on temporal scales: in parallel with the continuing refinement of weather forecasting models with increased skill, models that treat the longer-term dynamics inherent in climate studies have been advanced. In the process certain boundary conditions become incorporated as interactive components of the models; this is often the case where the increase in temporal scales logically forces "annexation" of what were initially external conditions (sea surface temperature is a good example). More recently, chemical processes are being included in transport codes that had their origin in weather and climate studies, so that today quite elaborate models are available to study the physical and chemical behavior of the atmosphere.

BOX 10.1

In the fall of 1994, the interagency Subcommittee on Global Change Research arranged for the special Forum on Global Change Modeling to provide an indication of the state of current progress in improving understanding of global change and to provide direction for future research. This forum served as a means of bringing together a representative set of scientists to develop a consensus statement on the credibility of global model estimates of future climatic change. The charge to those attending the forum and to those who submitted written comments was to develop a brief statement on the credibility of projections of climate change provided by general circulation models (GCMs) as background for potential interpretation of model results in the context of developing and considering national policy options. The focus of the forum was specifically on the climate aspects of the entire global change issue—thus not on the emission scenarios, the consequences of change to ecosystems and natural resource systems, or the socioeconomic implications and potential for responses. Still the results of the forum are of significant value to this chapter.

The forum identified a number of areas where sustained or intensified research efforts would bring important gains in understanding and predictive capabilities. As an overarching statement it was noted that "while progress is clear as a result of ongoing research efforts and important steps can be taken over the coming decade that will bring new insights, significant reductions of the uncertainties in projecting changes and trends in the climate will require sustained efforts that are very likely to require a decade or more."

"Progress will require significant effort because the problems are complex, because improvements in model parameterizations will require a sustained and long-term program of research and observations, and because the records of past changes and influences require careful reconstructions to make them more complete and more useful. Although progress may be modest, there are a number of processes and feedbacks on which research must be sustained because of the large leverage to be gained from improved understanding. These processes and feedbacks include:

- cloud-radiation-water vapor interactions, including treatment of solar and infrared radiation in clear and cloudy skies (also including resolution of uncertainties concerning anomalous solar absorption);
- ocean circulation and overturning;
- aerosol forcing, requiring information on aerosol character and extent;
- decadal to centennial variability;
- land-surface processes, including the climate-induced changes in the structure and functioning of ecological systems with resultant changes in global chemical cycles;
- short-term variability affecting the frequency and intensity of extreme and high impact events (e.g., monsoons, hurricanes, mesoscale storm systems, etc.);
- non-linear and threshold effects that create the potential for surprises; and
- interactions between chemistry and climate change and improved representation of atmospheric chemical interactions within climate models, thereby leading to improved understanding of the causes of trends in CH_4, N_2O, O_3, CFCs, and aerosols."[2]

Development of models for general circulation of the ocean started slightly later but has proceeded in a manner similar to that for the atmospheric models. Rather elaborate models that deal with the physics of the oceans are now available, and, as the preceding paragraph implied, ocean models have been linked to models of the atmospheric system. Within ocean models the inclusion of geochemical and biological interactions has begun, with a focus on the carbon cycle. Since the late 1960s, the geochemical aspects of the carbon cycle have been included in low-dimensional box models.[4] More recently, including the carbon-alkalinity system in general circulation models has simply been a question of allocation of computing resources. Modeling of the biological system, however, has been more challenging, and it has only been of late that primitive ecosystem models have been incorporated into global general circulation ocean models.[5] Even though progress has been significant, much remains to be done. Coupling difficulties remain between the ocean and the atmosphere (though the worrisome issue of flux correction is beginning to be resolved or at least better understood[c]). Fully eddy-resolving models with chemistry and biology need to be tested and validated in a transient mode. Finally, the prognostic aspects of marine ecosystems, including nutrient dynamics, need greater attention at basin and global scales.

Model development for the ocean and the atmosphere has had a fundamental theoretical advantage: it is based on the firmly established hydrodynamic equations. For example, the geostrophic constraint is particularly valuable. There is less constraint, however, on the dynamics of the global energy and water cycles, and at present there is far less theoretical basis for a "first principles" development of the dynamical behavior of the terrestrial system. We therefore need to develop a fundamental methodology to describe this very heterogeneous and complex system. For the moment it is necessary to rely quite heavily on parameterizations and empirical relationships. Such reliance is data intensive, and hence independent validation of terrestrial system models is problematical. Returning to the atmospheric models, which as noted are the most advanced dynamically, key processes like cloud formation remain too cloaked in parameterization.

Despite the difficulties that face modelers of terrestrial ecosystems, a coordinated strategy has been developed over the past five years to improve estimates of terrestrial primary productivity and respiration by means of measurement and modeling (see Box 10.1 and Chapter 2).[6]

For terrestrial ecosystems at the global scale, there has been a focus on the carbon cycle. This reflects demands on the science and advances in the theoretical foundation of the biogeochemical dynamics of terrestrial systems (at least under current conditions), and in this setting the strategy has begun to yield dividends. Several independent global models at mesospatial scales (roughly 50-

[c] This topic and others are discussed more fully in subsequent sections.

BOX 10.2

Global scales, The Global Analysis, Interpretation, and Modeling (GAIM) task force of the International Geosphere-Biosphere Program (IGBP) initiated an international model intercomparison, carried out through two workshops hosted in June 1994 and July 1995 at the Potsdam Institut für Klimatologie (PIK), in Potsdam, Germany. The purpose of the Potsdam workshops was to initiate and support a series of model intercomparisons by the various modeling teams that are currently modeling the terrestrial biosphere at the global scale. More than 15 models and modeling teams have participated in the intercomparison. One, but not the only, focus in the intercomparison was NPP, which is central to models of the global carbon cycle. There are significant differences in the calculation of NPP between current global biosphere models, and a particular focus of Potsdam '95 was to compare model parameters and outputs using standard input datasets to determine patterns and hopefully the causes of the variability. A fundamental problem in assessing the results of terrestrial ecosystem models, which are used to provide NPP intercomparisons, is a lack of good validation data.[7]

Continental scales. The Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) is comparing models of vegetation distribution, biogeochemistry, and biogeography for the conterminous United States under current and GCM-simulated future climates. In addition to changes in climate, the models are tested in response to changes in the chemistry of the atmosphere, in particular, to changes in the CO_2 concentration and to changes in nitrogen deposition. VEMAP is also conducting factorial experiments under different forcings and thereby setting the stage to tests under multiple stresses.[8]

km grids) now exist, and others are in various stages of development. With the one-half degree gridscale, it is now possible to investigate the magnitude and geographic distribution of primary productivity on a global scale by a combination of monitoring by remote sensing and modeling of the biogeochemical aspects of terrestrial ecosystems. These models range in complexity from fairly simple regressions between key climatic variables and biological production to quasi-mechanistic models that attempt to simulate the biophysical and ecophysiological processes occurring at the plant level (including their scaling to large areas). A fundamental difficulty remaining is the evaluation and perhaps validation of such models at the global scale. The interim step of model intercomparison has been taken (see Box 10.2). Other important model intercomparison projects currently under way include the Atmospheric Model Intercomparison Project, the Coupled Model Intercomparison Project, and the Paleoclimate Model Intercomparison Project.[9]

During the next decade, we need to expand our efforts in domain-specific models. In the ocean we need to improve our understanding of the controls on thermohaline circulation, of the potential changes in biological productivity, and of the overall stability of the ocean circulation system. Within terrestrial systems the question of the carbon sink-source pattern (what it is and how it might change) is central. Connected to this question is the development of dynamic vegetation models, which treat competitive processes within terrestrial ecosystems and their response to multiple stresses. For the atmosphere, a central question has been, is, and likely will continue to be the role of clouds. Further, increased efforts will be needed to link terrestrial ecosystems with the atmosphere, the ocean with the atmosphere, the chemistry of the atmosphere with the physics of the atmosphere, the land to the ocean, and finally the human system to the physical and biogeochemical subsystems.

In considering coupling atmospheric general circulation models (GCMs) to terrestrial models, where the coupling transfers not only energy and water but also important gases such as CO, CH_4, and CO_2, temporal and spatial scale issues again emerge. Energy, water, and CO_2-O_2 are actually exchanged across short timescales and exhibit a high degree of variability. Moreover, the gross fluxes are large in comparison with the net ecosystem fluxes, and hence the macro-balance of terrestrial carbon stocks, which determines the net flux of CO_2, is difficult to derive by direct integration of the gross fluxes. Ecological changes, such as successional sequences of tree species, are not treated well on time steps that are appropriate for considering photon input, water exchange, or trace gas fluxes and require significant intermediate parameterizations or models. Longer time step integrations have generally been more successful for carbon dioxide. On the other hand, the flux of CH_4 and other short-lived species cannot be treated by simple mass balance and crudely time-averaged responses.

The relatively simple problem of coupling land hydrology to the atmosphere remains elusive and yet is quite important. Water balances influence the exchanges of energy and many reduced gases (e.g., CH_4 depends on soil moisture conditions). Modeling sensitivity studies[10] have shown that if evapotranspiration were turned off over continental-scale areas, summer precipitation would be severely reduced and temperatures would be as much as 10 degrees (K) higher than with normal fluxes. They also show that over tall vegetation the integrated resistance to transpiration implied by the stomata will have a major effect on Bowen ratios over the diurnal cycle. Since the rates of sensible heat exchange over the diurnal cycle determine the height reached by the planetary boundary layer and thus diurnal variations of precipitation in tropical and summer conditions, it is evident that the inclusion of the role of vegetation is important for simulations of the hydrological cycle. Better field data are helping to establish the parameters needed for linking plant physiology to surface evapotranspiration. Considerable further effort is needed before the appropriate submodels can be applied with confidence over a wide range of vegetation cover.

The hydrological coupling between the land and the ocean has seen significant advances in the past 10 years, but we are still challenged to develop a more complete biogeochemical coupling. The difficulties are several: (1) there is a lack of data about the loss of important chemical compounds, such as organic carbon and nitrogen compounds, from terrestrial systems and aquatic systems; (2) we are uncertain how these exchanges might change in the face of land use change or climate change—more generally under pressure of multiple stresses on terrestrial systems; and (3) there is inadequate process-level understanding and supporting data on how these organic compounds are processed within the wide range of river systems.[d]

The coupling between the ocean and the atmosphere is central to the question of climate change. Atmospheric GCMs with prescribed oceans, long the mainstay of three-dimensional climate modeling, are inherently incapable of simulating the actual time-evolving response of the climate system to increasing greenhouse gases because this response involves heat uptake by the oceans. This is particularly clear when one realizes that the heat capacity of the atmosphere is roughly equivalent to that of the upper 3 m of the ocean. Fortunately, the scientific community has recognized for some time that if we are to penetrate the transient behavior of climate change we must produce credible coupled ocean-atmosphere models. Significant progress has been made in treating this demanding challenge on timescales of decades to centuries (see Box 10.3). Moreover, we have now demonstrated potential predictive skill in modeling the El Niño-Southern Oscillation (ENSO),[12] where the ocean-atmosphere system responds in a coupled fashion on interannual timescales. Finally, on very long timescales, we are probing the coupled ocean-atmosphere system for which paleo-oceanographic investigations suggest that aspects of longer-term climate change are associated with changes in the ocean's thermohaline circulation.

As we seek to couple better the chemistry of the atmosphere with the physics of the atmosphere, for instance, by adding the important chemical constituents and reactions to an atmospheric GCM, the issues of scale and computational challenges become daunting for transient calculations. Many of the important chemical reactions depend on concentration and hence on grid scale. In addition, important processes often occur in the boundary layer, which generally is not adequately resolved. Adding atmospheric chemistry to a GCM thus places greater demands on the terrestrial and oceanic boundary conditions and dynamic simulations. As in most of the other areas, progress will depend in part on the availability of advanced computing facilities (and in the more distant future petaflop machines[13]).

Finally, global climate and environmental changes often reflect the consequences of human actions superimposed on natural variability and change. It is

[d] Certainly there are river systems that are well studied, and there is knowledge of general patterns of carbon and nutrient processing in rivers; however, there remain large gaps in both our observational records and in our understanding when we face the issue on continental to global scales.

Box 10.3 Effects of Anthropogenic Carbon Dioxide Emissions on the Atmosphere-Ocean System

In 1967 Syukuro Manabe and Richard Wetherald published what is now regarded as one of the first credible calculations of the possible effect of increased carbon dioxide on climate. They calculated that a doubling of atmospheric carbon dioxide would warm the Earth's surface by about 2°C. This result laid the foundation for what has become an international multidisciplinary research effort on global warming.

In a recent paper, published 26 years after Manabe's pioneering one-dimensional CO_2 sensitivity study, he and Ronald Stouffer used a three-dimensional coupled ocean-atmosphere model to examine possible CO_2-induced climate changes over several centuries (see Figure 10.2).[11] Earlier studies had focused on shorter time horizons. In their scenario, CO_2 quadruples over a period of 140 years, then no longer increases. This perturbation is enough to cause the ocean's global thermohaline circulation to almost disappear in the model (though in some experiments it reappears given sufficiently long integration times). This circulation is important because in the present climate it is responsible for a large portion of the heat transport from the tropics to higher latitudes. In addition, Manabe and Stouffer's study indicates that sea level continues rising steadily for centuries after the CO_2 increase is halted. From this perspective, global climate change can no longer be viewed as just a problem of our own lifetimes but as a legacy—with uncertain consequences—now being passed forward to many future generations.

clear that humans can cause environmental change, even on a global scale. It is equally clear that environmental changes, whether human caused or not, can have impacts on humans. To understand these changes and to provide useful guidance to inform policy development and decision making will require increasingly integrated understanding of the diverse human and nonhuman components of the Earth system.[e] Environmental and climate change research must focus on predictions of key state variables such as rainfall, ecosystem productivity, and sea level that can be linked to estimates of economic and social impacts of possible environmental and climate change. Projections of emissions, land use, and other contributions must be related to underlying economic, technological, social, and political forces to understand linkages from causes to effects and back to causes. Uncertainties in the social side of the system, though of different character, are thus linked with the uncertainties of environmental and climate systems and are as important for understanding system behavior and informing decision making.

[e] For instance, global climate change is the subject of policy debate in most nations and of negotiations at the Conference of Parties and the Framework Convention on Climate Change. This is an obvious area that centrally requires the human component of the Earth system.

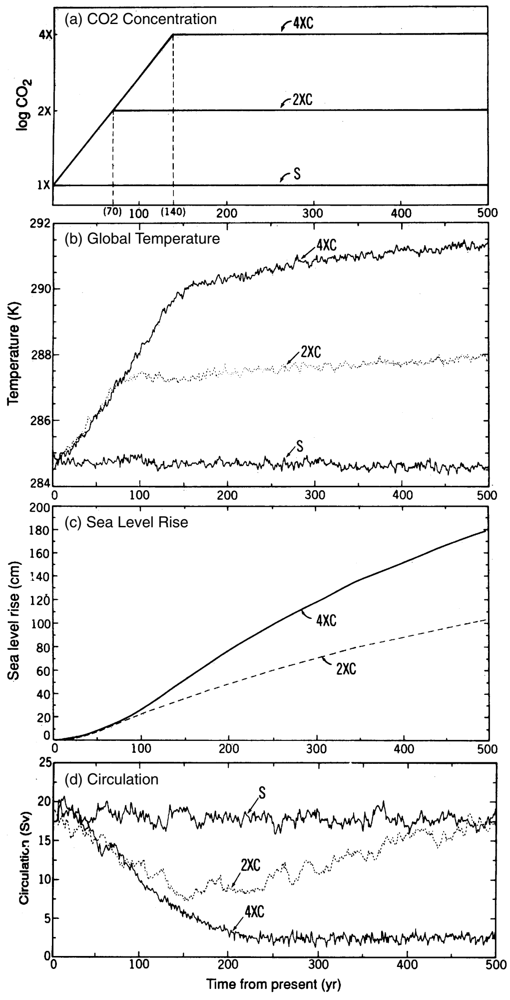

FIGURE 10.2 Impact of increasing CO_2 on the Earth's climate as simulated in a Geographical Fluid Dynamics Laboratory coupled ocean-atmosphere climate model. Shown are time series of (a) prescribed CO_2 concentration on a logarithmic scale in comparison to present levels; (b) global mean surface air temperature (°C); (c) global mean increase of sea level (cm) due to thermal expansion; and (d) intensity of the North Atlantic Ocean's meridional overturning circulation (10^6 m^3/sec). The labels "S," "2XC," and "4XC" refer to separate experiments in which CO_2 either remains constant (S) or increases at a rate of 1 percent per year (compounded) to double (2XC) or quadruple (4XC) the current concentration. Note that the sea level rise estimates do not include the effect of melted continental ice sheets. With this effect included, the total rise could be larger by a substantial factor. SOURCE: Manabe and Stouffer (1993). Courtesy of Macmillan Magazines Ltd.

In closing this introduction we state again that exciting and encouraging progress over this first decade of the USGCRP has been made in coupling parts of the major subsystems. Results from linking atmosphere and ocean GCMs reported in the literature show significantly different behavior than simulations in uncoupled models. The inclusion of biology in ocean GCMs has begun, but the biology remains rather simplistic, and we have yet to obtain results that include climatic feedback on the biology in the coupled system. Similarly, representations of linked terrestrial-atmosphere systems are in use, though the focus tends to be only on water and energy,[f] and the biology is still quite primitive; however, even now, revealing and unexpected teleconnections are being discovered. Finally, progress is being made toward model structures and datasets that will allow implementation of atmosphere-ocean-terrestrial models that include key biological-biogeochemical feedbacks.[14] There is also encouraging early work in developing integrated assessment models that couple economic activity with associated emissions and impacts and with models of the biogeochemical and climate subsystems. This work has yielded some preliminary insights into system behavior, potential policy responses, and key policy-relevant uncertainties.[15]

In the next decade we should continue and expand on this record of progress by investigating the perplexing issues framed by current coupled model experiments (e.g., the use of flux correction in coupled ocean-atmosphere models); conducting careful delimited experiments in which new linkages are explored (biogeochemical-energy-water linkages between the terrestrial system and the atmosphere); adding specific subsystems to existing linked model experiments (e.g., adding a marine biosphere model to coupled ocean-atmosphere carbon GCMs); and exploring and testing full-ensemble runs of coupled complex models. In this spirit and in recognizing the formidable tasks ahead, this chapter discusses future development of Earth system models in terms of four interface challenges: the atmosphere-terrestrial: energy, water, biogeochemical subsystem; the terrestrial-ocean: water and biogeochemical connection; the atmosphere-ocean-marine biosphere; and the physical atmosphere and the chemical atmosphere. The following sections present a brief general discussion of the current status of the currently available models at these four interfaces and of the challenges of the interface per se (see Box 10.4). The chapter concludes with a consideration of the overarching challenge: linking the biogeochemical and physical-climate subsystems with the human subsystem.

[f] Atmosphere-terrestrial systems focused on carbon and/or trace gases tend to have only one-way coupling (atmospheric forcing) and do not yet include critical biogeochemical feedbacks.

BOX 10.4

The 1994 Special Forum on Global Change Modeling found that "[i]mproving the linkages coupling the atmosphere, oceans, and land surface will reduce uncertainties in estimates of the overall climate response by improving the accuracy of the climate simulations, by eliminating the need for ad hoc adjustments to fluxes between components that are used in some models, and by allowing fuller exploration of natural climate variability over all timescales."

The basis for this is simply that "climate is a result of the complex interactions of the atmosphere, the oceans, and the land surface. The dynamics, thermodynamics, and hydrodynamics (and to an increasing extent the chemical and vegetation dynamics) must all be treated in order to provide a realistic simulation of climate. The focus has initially been on the atmosphere, then increasingly on the ocean; coupling of the atmosphere and oceans has not been completely successful due to limitations in understanding of ocean mixing and air-sea exchange mechanisms, in addition to limitations in model resolution and the full range of processes internal to each domain. Increased attention to improved representation of the coupling is starting to lead to improved representations of temperature and other climatic variables. Corresponding improvements are needed in representations of the land surface and land atmosphere interactions and fluxes. Because vegetation and chemical composition can affect radiative forcing and water vapor concentrations, these must also be treated in coupled simulations. The emerging results from the World Ocean Circulation Experiment (WOCE), the Global Energy and Water Cycle Experiment (GEWEX), and other field and analysis programs are providing the opportunity for improving the performance of coupled models."[16]

THE TERRESTRIAL-ATMOSPHERE SUBSYSTEM

Overview

Interactions between terrestrial ecosystems and the troposphere are important components of the linkage of the land biosphere and the atmosphere. The most obvious interaction is the water-energy cycle. Water entering terrestrial ecosystems directly affects plant growth, soil water properties, recharge of groundwater pools, and discharge into river systems. Water is redirected back into the atmosphere through the processes of canopy interception, followed by evaporation, transpiration, and direct soil evaporation, all of which moderate surface temperatures and provide a mechanism to recycle water for further precipitation. Elements of the water balance also regulate the terrestrial-atmosphere exchanges of carbon and nitrogen on both continental and local scales.

The metabolic processes that are responsible for plant growth and maintenance and the microbial turnover associated with dead organic matter decomposition move carbon, nutrients, and water through plants and soil on both rapid and intermediate timescales. Moreover, these cycles affect the energy balance and provide key controls over biogenic trace gas production. Some of the carbon fixed by photosynthesis is incorporated into plant tissue and is delayed from returning to the atmosphere until it is oxidized by decomposition or fire. This slower carbon loop through the terrestrial component of the carbon cycle, which is influenced by cycles of nutrients required by plants and decomposers, affects the rate of growth of atmospheric CO_2 concentration and imposes a seasonal cycle on that trend (see Figure 2.10, Chapter 2). The structure of terrestrial ecosystems, which respond on even longer timescales, is the integrated changes to climate and to the intermediate timescale carbon-nutrient machinery. The loop is closed back to the climate system, since it is the structure of ecosystems, including species composition, that largely sets the terrestrial boundary condition in the climate system in terms of surface roughness, albedo, and latent heat exchange.

In sum, terrestrial ecosystems influence climate and biogeochemical cycles on several temporal scales that involve feedback loops that may modify the climate and biogeochemical system dynamics. Climate change will clearly drive vegetation dynamics; however, vegetation changes in amount or structure feed back to the climate system through changing water, energy, and gas exchange. Biogeochemical cycling will also change, altering the exchange of CO_2, CH_4, and other greenhouse gases, which further closes the loop back to the climate system.

Modeling the interactions between terrestrial and atmospheric systems requires coupling successional models to biogeochemical models to physiological models that describe the exchange of water and energy between vegetation and the atmosphere at fine timescales. There does not appear to be any obvious way to allow direct reciprocal coupling of GCM-type models of the atmosphere, which inherently run with short time steps, directly to ecosystem or successional models, which influence climate but have coarse temporal resolution, without the interposition of physiological and biogeochemical models. This coupling across timescales represents a nontrivial problem that sets the focus for the modeling strategy.

A Modeling Perspective

Intuitively, we might develop a global model of terrestrial ecosystem dynamics by combining descriptions of each of the physical, chemical, and biological processes involved in the system. In such a scheme, longer-term vegetation changes would be derived by integrating the responses of the rapidly evolving parts of the model. However, we cannot estimate productivity of whole plants, let alone entire ecosystems by simply integrating models that describe the rapid processes of CO_2 diffusion, photosynthesis, fluid transport, respiration, and transpiration in cells and leaves. Carbon dioxide fluxes are strongly linked with water fluxes, and whereas we may treat water flux on fine temporal scales, the accumulation aspect (i.e., growth of plants) strongly suggests that we treat carbon and water differently when spatial and temporal scales are extended. At fine spatial scales, such as the scale of a forest watershed, there is often coherence between water, energy, and carbon. Terrestrial models of water and energy exchange between the atmosphere and land surface operate at the subhourly to daily timescale, as do models of net photosynthesis.[17] However, biogeochemical models capable of extrapolation over large spatial scales generally operate at weekly to monthly timescales with finer-scale dynamics being used as constraints.[18] To properly model the exchange of water, energy, and important biogeochemical elements like carbon and nitrogen between the atmosphere and the land surface, it will be necessary to resolve differences in both temporal and spatial scale between linked atmospheric and biogeochemical models. In addition, the spatial averaging implied in the selection of parameters and processes to consider is difficult because of nonlinearities—that is, the choice of scale influences the calculation of averages, which can have significant and unexpected effects on results.

A nested treatment has been suggested to deal with interactions on a hierarchy of temporal scales.[19] For example, the metabolic activities of terrestrial plants associated with growth and maintenance constitute the fastest interactions, on the order of seconds to days and determine latent heat, energy, water, and CO_2 gas exchange through gross photosynthesis and respiration. Intermediate processes, from days to weeks, include the development of leaf area (with a characteristic carbon density), soil water balances, trace gas exchanges, and decomposition of organic soil materials. Longer-term annual time steps encompass net primary productivity, ecosystem production, and long-term changes in carbon and nutrient pools in plant tissue and soils. Similar and parallel strategies could be used for spatial scaling.

At each step toward longer timescales the climate system integrates the more fine-scaled processes and applies feedbacks onto the terrestrial biome. At the finest timescales the influence of temperature, radiation, humidity, and winds has a dramatic effect on the ability of plants to transpire. On longer timescales, integrated weather patterns regulate biological processes such as timing of leaf emergence or excision, uptake of nitrogen by autotrophs, rates of organic soil decay, and turnover of inorganic nitrogen. The effect of climate at the annual or interannual scale defines the net gain or loss of carbon by the biota, its water status for the subsequent growing season, and even its ability to survive.

As the temporal scale is extended, the development of dynamic vegetation models, which respond to both climate and human land use as well as other changes, is a central issue. These models must treat not only successional dynamics but also ecosystem redistribution. For example, following the abandonment of agricultural land, fluxes and pools of carbon, nitrogen, and phosphorus in secondary vegetation often do not attain the same levels as found in "undisturbed" natural vegetation. The recovery of natural vegetation in abandoned areas depends on the intensity and length of the agricultural activity and the amount of soil organic matter on the site at the time of abandonment. To simulate the biogeochemistry of secondary vegetation, models must capture patterns of plant growth during secondary succession. These patterns depend substantially on the status of nutrient pools inherited from the previous stage. The changes in hydrology also need to be considered, since plants that experience water stress will alter the allocation of carbon (e.g., to allocate more carbon to roots). Processes such as reproduction, establishment, and light competition have been added to such models and interact with the carbon, nitrogen, and water cycles. Disturbance regimes such as fire are also incorporated into the models, and these disturbances (and potential changes in their frequency) are essential to include in order to successfully treat competitive dynamics and hence future patterns of ecosystem distribution. It should also be noted that these forcing terms themselves may be altered by the changes that result from changes in the terrestrial system. Finally, the issues of successional dynamics, which result from extending the temporal scale, also force more careful consideration of spatial scaling.

Research Priorities

Immediate challenges that confront models of the terrestrial-atmosphere system include exchanges of carbon and water between the atmosphere and land and the terrestrial sources and sinks of trace gases. An overarching grand challenge is to provide insight into the dynamics of a biosphere subjected to *multiple stresses*, which after all is the actual case that we confront (see Chapter 2). Hence, the development of dynamic vegetation models is, as stated, of central importance.

Carbon

In the past two decades the significant influence of the terrestrial biosphere on the global carbon balance and hence on the problem of timing and magnitude of possible climate change has been recognized.[20] Much of the remaining uncertainty in our understanding of the carbon cycle centers on the role of terrestrial ecosystems, in which at least two factors govern the level of carbon storage. First and most obvious is the anthropogenic alteration of the Earth's surface—for example, through the conversion of forest to agriculture—which can result in a net release of CO_2 to the atmosphere. Second, and more subtle, are the possible changes in net ecosystem production (and hence carbon storage) resulting from changes in atmospheric CO_2, other global biogeochemical cycles (*particularly nitrogen*), and/or the physical climate system.

The productivity of the terrestrial biosphere is primarily controlled by the radiation reaching terrestrial ecosystems, the availability of nutrients, and the climatic conditions in which they live, that is, by the conditions under which plants carry out photosynthesis and allocate photosynthates to various structural components. Precipitation and temperature primarily govern the absorption of photosynthetically active radiation and its conversion into dry matter—that is, the net primary productivity (NPP) of the biosphere. Nitrogen and changes in its availability, as well as changes in other nutrient cycles, are the key biogeochemical controls on productivity.

At present, several rather complex models are being developed to account for the ecophysiological and biophysical processes that determine the spatial and temporal features of NPP.[21] Their goal is to provide a prognostic capability. The major modeled processes are photosynthesis, growth and maintenance respiration, evapotranspiration, uptake and release of nitrogen, allocation of photosynthates to the various parts of the plant, litter production and decomposition, and phenological development. Some models focus on detailed mechanistic relationships for some processes (e.g., water and CO_2 fluxes and the nitrogen cycle), while others rely on simple empirical relationships or satellite observations to derive or constrain important features (e.g., canopy characteristics and phenology).

The challenge is not simply to calculate NPP but rather to develop coherent explanations for past changes in the total carbon fluxes and/or storage, to test hypotheses about the underlying causes of these changes, and to establish the capability for estimating future changes. It is now becoming evident that models of the terrestrial carbon cycle and of terrestrial ecosystem processes in general will play an overriding role in addressing many of the issues posed by global environmental change. The question of climate change is a case in point. Describing, characterizing, and eventually understanding and predicting the spatial patterns of changes in terrestrial carbon storage and associated fluxes are essential to the assessments undertaken by the Intergovernmental Panel on Climate Change (IPCC[22]).[23] These patterns and allied issues lie at the heart of analyzing any atmospheric CO_2 stabilization policy.[24] Moreover, these issues must be far better resolved if there is to be an adequate verification scheme to confirm national performance in meeting targets for CO_2 emissions. From a broader perspective, the prognostic models of terrestrial carbon cycle and terrestrial ecosystem processes are central for any consideration of the effects of environmental change and analysis of mitigation strategies; moreover, these demands will become even more significant if countries begin to adopt carbon emission targets.[25] Finally, while progress will be made (and is needed) on modeling terrestrial processes, more integrative studies also are needed wherein terrestrial systems are coupled to models of the physical atmosphere and eventually to the chemical atmosphere as well.[26] Tying in the human component is clearly important.[27]

Soil Moisture

Modeling studies of extreme (theoretical) deforestation in the Amazon region have indicated a severe weakening of the water cycle attributable solely to changes in roughness and albedo at the land surface.[28] As noted above, the Earth's climate regulates the distribution of ecosystems, which in turn modifies land surface properties such as surface roughness and albedo, which then feeds back on the climate system. Elements of the water balance also regulate the carbon and nitrogen cycling on both continental and local scales.[29] As such, soil moisture is a key component in the land surface schemes in GCMs, since it is closely related to evaporation and thus to the apportioning of sensible and latent heat fluxes. Accurate prediction of soil moisture is crucial for simulation of the hydrological cycle and of soil and vegetation biochemistry, including the cycling of carbon and nutrients at local, regional, continental, and global scales. It thus plays a significant role in atmospheric models, hydrological models, and ecological models.

Unfortunately, there exist large differences between models of soil moisture even for simulation runs with high-quality atmospheric forcing data in carefully chosen parameters.[30] Therefore, the prediction of future soil moisture through coupled terrestrial-atmosphere models cannot be considered reliable, especially since the forcing data are necessarily inaccurate and the information required for specifying land surface parameters is crude. Moreover, current land surface schemes differ profoundly between models in terms of their structure and their treatment of various land surface processes such as evaporation, transpiration, and drainage; it appears that differences in scheme structure are of particular importance.[31]

The differences among present land surface schemes[32] used in models are manifested in a number of ways:

- Different annual equilibrium when forced with the same atmospheric forcing data and the same land surface parameters.
- Different descriptions of the seasonal cycle of soil moisture. The greatest dispersion occurs when vegetation contributes to the total evaporative flux, when there is a great atmospheric demand, and when the available soil moisture is limited.
- Different partitioning of incoming precipitation among runoff-drainage, soil storage, and evaporation depending on timing and antecedent conditions.

Most schemes can be tuned to observations, but no single scheme predicts well all of the variables describing the land surface hydrology. Indeed, the consensus (single average) of all participating schemes generally outperforms any individual scheme. This suggests that individual schemes capture specific aspects of this complex system well but that no scheme yet captures the whole system satisfactorily and consistently. This issue is important and deserves attention.

As noted above, critical improvements in ecosystem modeling and its linkage to Earth system models will require the development of schemes for integrating together processes with very different rates of change. This implies the continued development and validation of physiological, biogeochemical, and successional/population models that are capable of representing the range of processes and communities found in ecosystems worldwide. Experiments with coupling these three levels of models are required, as are tests of the models when run interactively with atmospheric models. The different levels of models have differing data requirements, and these must guide the collection and archiving of data. This topic resurfaces in the subsection that addresses modeling perspectives at the mesoscale in the land-ocean subsystem discussion later in this chapter.

Trace Gases

The broad question is the role of terrestrial ecosystems and human activities in the regulation of atmospheric concentrations of CO_2 and other radiatively active atmospheric constituents. Understanding of these influences is still partial, but it will be essential to understanding the likely future consequences of fossil fuel burning, industrial emissions, and land use changes. Key issues include the following:

- Developing and validating a suite of trace gas source models and coupling these models to atmospheric GCMs and atmospheric chemistry/transport models (see the atmospheric physical-chemical subsystem discussion in this chapter) to predict atmospheric composition and its latitudinal gradients under changed climatic boundary conditions.
- Developing a predictive model for the distribution, growth/decay, and functionality of wetlands, based on water balance, topography, and surface hydrology.

There are also three paleo challenges:

- Documenting and explaining the time course of changes in CO_2 versus CH_4 during periods of rapid climate change, including the last deglaciation and early Holocene.
- Explaining the atmospheric composition at the last glacial maximum, when concentrations of major measured greenhouse gases (CO_2, CH_4, N_2O) were exceptionally low while concentrations of both soluble and insoluble mineral dust over the land, ocean, and ice sheets were extraordinarily high.
- Clarifying the sources and transport of mineral dust from the terrestrial surface and its possible implications for (a) radiative forcing in the atmosphere and (b) marine primary production and subsequently the implications for glacial-interglacial changes in climate and atmospheric CO_2, respectively.

In sum, we need global-scale, process-based modeling of terrestrial biogenic fluxes of CH_4, CO, N_2O, nonmethane hydrocarbons, and NO_x and their responses to changes in climate and NPP (including effects of CO_2 that may provide coupling between CO_2 changes and other trace gas fluxes).

Finally, as previously stated, it is essential that we expand our ability to model *multiple stresses* on terrestrial ecosystems and how the effects of such multiple stresses might ripple back through other components of the Earth system. We will not understand the carbon cycle without addressing changes in the nitrogen and water cycles. The effect of climate change cannot be divorced from the ongoing human alteration of the terrestrial biosphere through land use change. Further, land use change affects the terrestrial dynamics and controls on water, carbon, and nutrient cycling. The issues of multiple stresses are described in detail in Chapter 2 (see also Chapter 7).

THE LAND-OCEAN SUBSYSTEM

Overview

The availability of water is an important regulator of plant productivity and sustainability of natural ecosystems. In turn and as previously noted, terrestrial ecosystems recycle water vapor at the land surface/atmosphere boundary, exchange numerous important trace gases with the troposphere, and transfer water and biogeochemical compounds to river systems. This section[33] focuses on this latter exchange and addresses the development of models to explore the possible changes in fluxes in rivers of water, carbon, nitrogen, phosphorus, and silicon from terrestrial biomes to the world's oceans.

River systems are linked to regional and continental-scale hydrology through interactions among soil water, evapotranspiration, and runoff in terrestrial ecosystems. River systems and, more generally, the entire global water cycle control the movement of constituents over vast distances from the continental land masses to the world's oceans and, as discussed in the previous section, to the atmosphere. The system serves in part to transfer nutrients to the marine biological system and hence affects oceanic productivity. Landscape disturbance greatly increases the rate of loss from the terrestrial biosphere,[g] particularly with respect to nutrients and sediment. This redistribution is important to both donor (landscape) and recipient (aquatic) ecosystems. Tools must be developed to quantify these phenomena and provide prognostic insight.[34]

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[g] On shorter (less than decades) timescales the effect on marine production is primarily on coastal ecosystems, whereas on longer timsescales (centuries) the effect could be on the oceanic system generally.

The primary emphasis of this section is on modeling the fluxes and transformations of water and of biologically important constituents derived from terrestrial ecosystems, namely, carbon, nitrogen, phosphorus, and silicon. Both dissolved and particulate fractions must be considered, and attention must be paid to the physical transport of sediments. Since these materials are transported through groundwater, rivers, lakes, and wetlands, an analysis of water balances and water fluxes will be essential. Micronutrients, major cations and anions (e.g., SO_4, Cl, Ca, Mg, K, Na), and weathering products such as carbonate are important in establishing overall material balances and may be crucial as missing trace nutrients (e.g., the question of iron in the surface waters of the South Pacific). However, given the complexity of the topic, these are considered secondary issues for this discussion.

The drainage basin serves as a key organizing principle in this discussion. The overarching issue is to understand and model how specific terrestrial-derived materials are mobilized, delivered to, and transformed along the full cascade of landscape-fluvial systems. Adequate consideration must be given to terrestrial ecosystem dynamics, the role of wetlands, and interactions in the river-riparian complex. The downstream boundary consists of the landward margin of the coastal zone.[h] Interconnections with atmospheric boundary forcing (predominantly through climatic variables), atmospheric deposition, and CO_2 enrichment also are relevant, as are feedbacks to the atmosphere through CO_2 and trace gas emissions from aquatic and wetlands ecosystems (both treated in the previous section). Addressing such linkages is necessary to define the integration of drainage basin dynamics into a larger Earth system context. These linkages are also particularly important in more explicit coupling of the human system (which is discussed later) with the physical, chemical, and biological subsystems.

A Modeling Perspective

From a modeling perspective, several aspects need to be addressed. First, the cycling of water between land and atmosphere can produce a "residual" or runoff. This water forms the basis of rivers and the recharge of aquifers; moreover, by definition it is tied to the coupled dynamics of the terrestrial ecosystem and the land-atmosphere water cycle.[i] The drainage basin "transforms" complex pat-

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[h] In effect, consideration is then passed to the ocean-atmosphere section; however, the linkage through the coastal ocean of the inputs from the land at the land-(coastal) ocean boundary and the "open" ocean needs further consideration.

[i] Note, in Figure 10.1 it might appear that the land-atmosphere hydrological system is somehow "decoupled" from terrestrial (biogeochemical) ecological systems and the terrestrial-atmosphere physical climate/energy system. Rather, the diagram should be read as showing that the hydrological component (particularly soil moisture) tightly ties the dynamics of the atmosphere and the land.

terns of locally generated runoff into horizontal transport as rivers (see Figures 10.3 a and b). The drainage basin is the logical unit of organization; as its size is varied, the associated finite element grid varies in mesh size. Using the drainage basin as a focal unit allows a broad spectrum of fluvial systems to be considered. Although the focus is decidedly on the regional and larger domains, the legacy of research findings obtained at smaller scales provides an extraordinarily rich foundation.

The flow of water contains a variety of biogeochemical compounds (from point and nonpoint sources), and models must treat their internal processing in river systems (Figure 10.4). Thus, in addition to the transport of water and the associated loading of chemical constituents, the dynamics of the biogeochemical processes that act on constituents in the river must be treated. Finally, any global perspective on surface hydrology must explicitly recognize the impact of human intervention in the water cycle, not only through climate and land use change but also through the operation of impoundments, interbasin transfers, and consumptive use.

A long-term goal is to model a series of material transformations along the entire continuum of fluvial systems from the points of terrestrial mobilization to delivery and processing in the coastal zone. The transformation in and the progression through the drainage basin of constituents in various chemical states would be included in such models, paying particular attention to processes such as flocculation, settling, gaseous losses (such as denitrification), phosphate sorption and desorption, silicon uptake and release from siliceous organisms, degassing of water bodies, and so forth. The extent to which each biogeochemical process is specifically modeled would depend on the state of understanding, the availability of data, and the purpose for which the model was constructed. Multiple component models would be required dealing with terrestrial ecosystems (Chapter 2), river continuum concepts,[35] nutrient cycling,[36] and spiraling.[37]

Coupling of models between drainage basins and the near shore will also be necessary to provide a complete analysis of the interaction of terrestrial and coastal zone ecosystems. Such coupling may require coastal physical oceanographic models linked to biogeochemical process simulations of regional land-coastal margin ecosystems.[38] This issue is an important research topic in itself.

The issue of scaling cuts across the entire USGCRP and is particularly challenging in this area of the land-ocean subsystem. Three spatial scales need to be considered: macroscale, mesoscale, and microscale.

Macroscale

At the macroscale (10^5 to 10^7 km^2), linked models have been successfully used to compute runoff and river flow.[37] A water balance algorithm based on straightforward water budgeting procedures operating on single-grid elements provides the calculation of soil water availability and runoff for each time step from the difference between precipitation and evapotranspiration, in conjunction

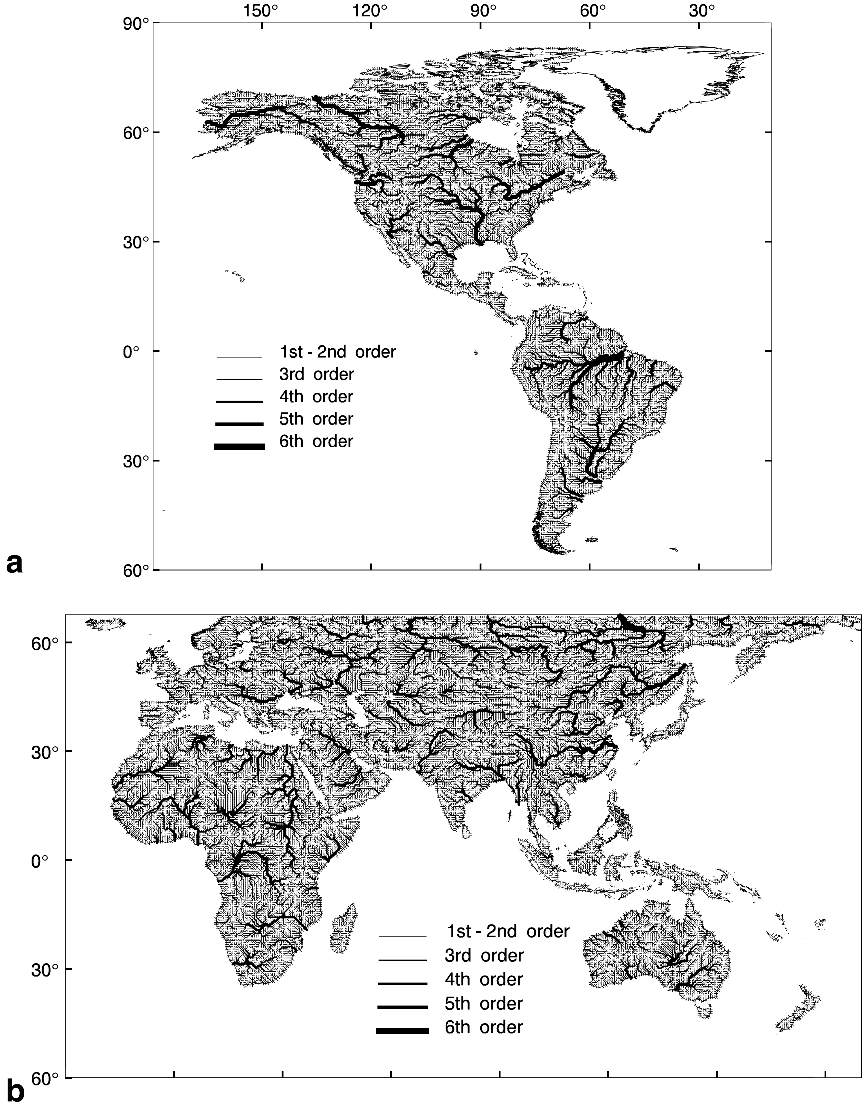

FIGURE 10.3 a and b The Simulated Topological Network (STN) for potential river systems at 30-minute (longitude × latitude) spatial resolution for (a) western and (b) eastern hemispheres. Each of 59,132 land-based grid cells is assigned a direction of flow and linked to adjoining cells. A total of 33,252 distinct river segments are topologically linked to define 6,152 individual STN-30p basins. Both exorheic (directed toward the ocean) and endorheic (internal drainage) networks are represented in this database. Order refers to individual river segments. SOURCE: Vörösmarty et al. (1998c). In review.

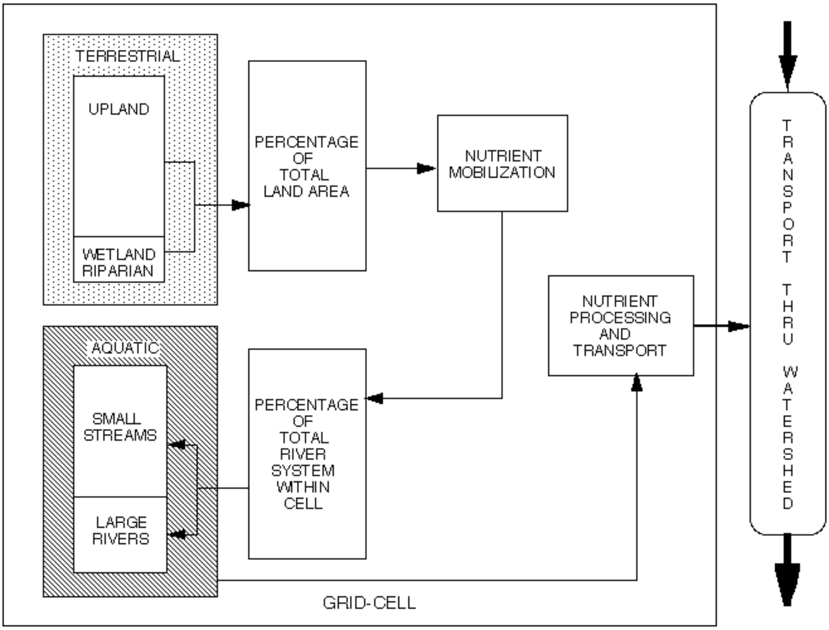

FIGURE 10.4 Conceptual terrestrial and aquatic processing model.

with a soil drying function.[j] These calculations have been recently enriched by the National Center for Environmental Prediction's reanalyses products, which improve estimates of vertically integrated atmospheric water vapor and wind fields. These provide estimates of time-varying atmospheric vapor content and convergence fields that, together with satellite-derived precipitation, will yield far better assessments of evapotranspiration.

Computed runoff from such single-grid elements is then routed using a set of simultaneous differential equations organized through a network topology (see again Figures 10.3 a and b). The transport algorithm is generally a quasi-linear cascade model that can be modified to accommodate wetlands inundation. This latter will be important in regions such as the Amazon, where realistic hydrographs cannot be generated without an explicit consideration of these intermediate wetlands effects, lasting typically about six months per year. In addition to meteorological forcings such as precipitation, temperature, and radiation, addi-

[j] We note the discussion in the previous subsection on soil moisture, which raises important modeling issues that impact these considerations on runoff.

tional data on soil texture, land cover, topography, wetlands location and extent, and river networks are required (see Figure 10.5). The performance of each function should be judged objectively by its ability to successfully produce runoff that can be checked against verifiable discharge records.

Mesoscale

Water balances at the intermediate mesoscale (10^4 to 10^5 km^2) form the crucial link between continental-scale gridded calculations and the fine scale, which is often needed for catchment-level impact assessment. In scaling up from the catchment responses (microscale; discussed below) to sequentially larger domains, investigators[40] have shown that the larger-scale modeling problem can be simplified by identifying dominant process controls on the water and energy balance and that the spatial variability of these important controls could be represented in a statistical-dynamical framework. These studies identified a representative elementary area (REA), or threshold scale, for runoff and energy balance modeling. At scales greater than the REA scale (which was determined to be 1 to 2 km^2), it was found that the statistical-dynamical model formulation yielded minimally biased simulation results as compared to more detailed spatially distributed simulations.

Investigators[41] proposed a general mesoscale model formulation that aggregates a simplified soil-vegetation-atmosphere transfer scheme with respect to a statistical distribution of topographic and soil properties. The resulting mesoscale hydrological model may significantly advance the issue of the appropriate land surface parameterization in climate models, which was highlighted in the soil moisture discussion in the land-atmosphere subsystem. This possible advancement stems from the fact that the approach differs greatly from the current generation of land surface parameterizations since it incorporates scale spatial variability in topography and soils on scales smaller than the mesoscale grid to model downslope redistribution of soil water. In addition to providing a realistic representation of runoff processes, the redistribution of subsurface soil water feeds back through the model structure to yield subgrid variability in the surface energy fluxes. These topics are clearly important and merit increased attention.

Microscale

As mentioned above, the problem of scaling up these traditionally local studies is receiving significant attention. At the catchment scale, these studies have shown that explicit patterns of spatially variable model parameters and inputs can significantly affect hydrological response and must therefore be incorporated into models applied across these scales. Consequently, the spatially distributed grid-based water and energy balance models could be used to simulate

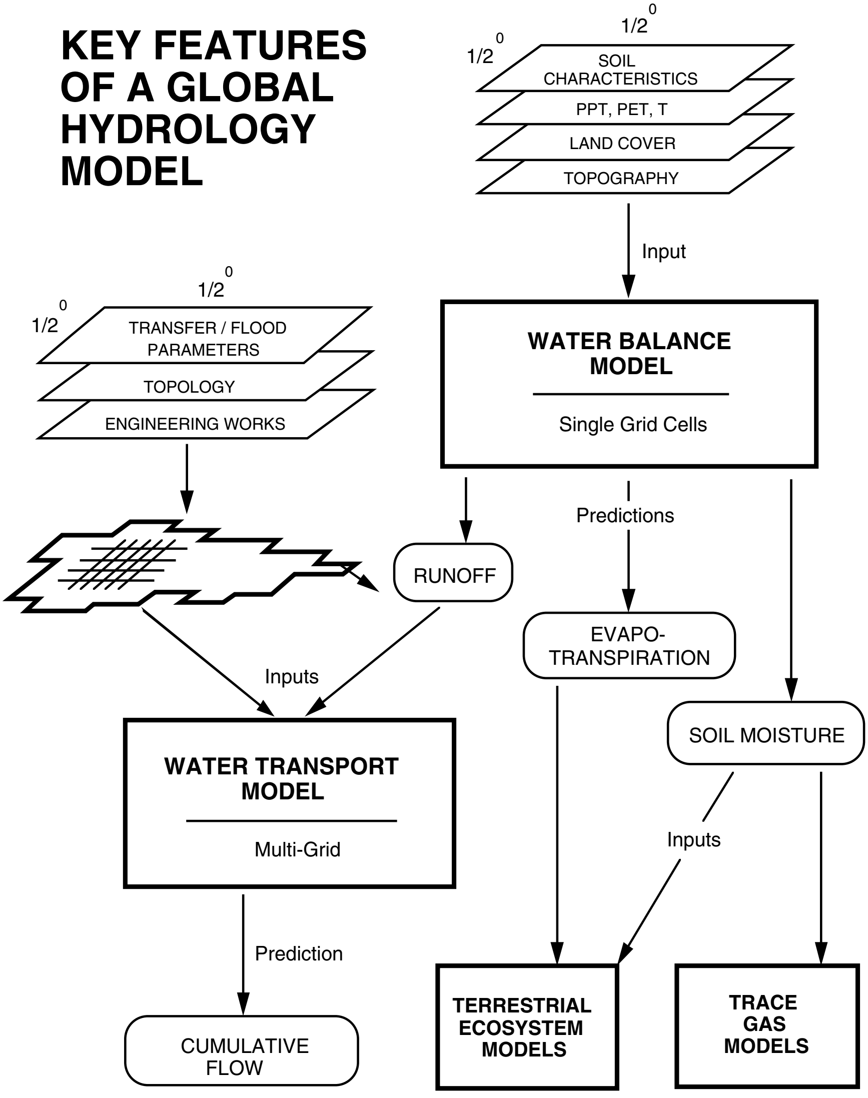

FIGURE 10.5 Key features of a global hydrology model. SOURCE: Vörösmarty et al. (1989). Courtesy of the American Geophysical Union.

the runoff and energy fluxes from small watersheds and thereby treat more accurately subgrid (in macromodels)-scale information.[k]

Research Priorities

Two overarching themes in the research priorities for the land-ocean subsystem are (1) the important issue of data availability and (2) concerns relating to scaling, particularly with respect to spatial scaling. The first issue is being aggravated by national concerns in certain areas about releasing hydrological data, and this concern is then reflected by international agencies that hold national data. The second issue is made more difficult by the extremely varying topography and soil structure across the rivers of the world. Fortunately, techniques from geographical information systems may allow the heterogeneity to be addressed directly.

Case Studies

It is important to recognize that several projects that can potentially contribute to the issues raised in this section are already in progress or are being planned, including for the Mississippi, the Global Energy and Water-Cycle Experiment Continental-Scale International Project;[42] for the Amazon, the Large-Scale Biosphere-Atmosphere Experiment;[43] and for the Atlantic drainages,[44] U.S. LMER sites.[45] These case studies should be focal points for developing land-ocean interface models. They should provide for the assembly and synthesis of catchment flux data, including the biogeochemical compounds of C, N, P, and Si.[46] They should also provide an assessment of the principal flux controls within the framework of both the first-order classification and the constituent budgets. These controls must explicitly consider the human component. A recent NRC report (1998), *Global Energy and Water Cycle Experiment (GEWEX) Continental-Scale International Project*, describes the substantial progress that has been made to characterize the variability of water and energy cycling in the Mississippi River basin and the importance of this information to improving water resource management.

Global Applications

Understanding secured through such case study work should be carried for-

[k] Model state variables include surface temperature, canopy water storage, soil moisture in two layers, and local water table depth as a bottom boundary. Potential evapotranspiration is computed from a nonlinear energy balance equation, and actual evapotranspiration is determined as the minimum of the potential and soil-vegetation-controlled moisture limitation. Soil properties are represented parametrically and with the additional assumption that saturated hydraulic conductivity declines exponentially with depth. Vertical soil water fluxes are represented using approximate analytical solutions to water flow in the unsaturated zone.

ward to the global scale and used to enrich this ongoing research. Fortunately, several global models of modern constituent fluxes already exist.[47] To check, verify, and begin validation of the transport models will require budgets of water and constituents for large basins of the world. This requires ground-based meteorology in tandem with remotely sensed data for a series of variables, including information on precipitation, soils, land cover, surface radiation, status of the vegetative canopy, topography, floodplain extent, and inundation.[48] It may even be possible to obtain hydrographics remotely. Model results can be constrained by using a database of observed discharge and constituent fluxes at key locations in the drainage basins analyzed.[l] These models can be coregistered to results obtained from ongoing global circulation modeling studies and thereby address the issue of climate change.

As noted above, it will be difficult to link individual processes whose respective scales encompass several orders of magnitude in space and time. This is particularly important in considering the river component of the global water cycle. The spatial resolution of current global climate models, typically 100 to 200 km, is too coarse to simulate the impact of global change on most individual river basins. Substantial efforts like the U.S. Department of Energy's (DOE) Computer Hardware and Advanced Mathematics and Model Physics[49] program are under way to increase global model resolution. An alternative to increasing the resolution of global models is to use climatic boundary conditions to drive regional models with sufficient resolution. On the other hand, transient climatic time series and monthly discharge data for past climate over several decades at selected locations provide the opportunity for important tests of models, including appraisal of the impact of episodic events, such as El Niño, on surface water balance and river discharge in South America.

A major extension of models of runoff and riverine transport will involve development of tandem constituent transport models for the transport and processing of both dissolved and particulate material to the coastal oceans. A major initial effort could be to model the mobilization and transport of carbon and nitrogen from the terrestrial landscape into fluvial ecosystems in drainage basins that include both natural and disturbed ecosystems.

Estimates of river fluxes and chemical signatures depend on existing data resources around the globe. It will be necessary to inventory, document, and make available such datasets, to identify gaps in our knowledge and, where necessary, to collect additional data. A partial inventory of riverborne constituent data indicates that the most abundant data resources are available only for highly developed countries. Rapidly developing regions show an intermediate level of

[l] The World Meteorlogical Organization-sponsored Global Runoff Data Center in Koblenz, Germany, is an important partner in a global hydrologically oriented geographic information system; however, there is growing concern about the open availability of the data.

data availability, while less developed countries are most poorly monitored. Even in the best-represented regions of the globe, however, coherent time series are available for only the past 30 years or less, constraining our ability to construct and test riverine flux models. Data quality is yet another issue limiting the usability of water quality data. Standardized protocols, both in terms of sampling frequency, spatial distribution of sampling networks, and chemical analyses are still needed to ensure the production of comparable datasets collected in disparate parts of the globe. Several upgrades of the basic monitoring system for discharge and riverborne constituents at the large scale are therefore required.

In sum, these efforts in both case studies and global applications will permit us to understand in more detail current and future patterns of landscape impoverishment as well as eutrophication of inland waters. Moreover, at both the river basin specific and the continental to global scales, the model outputs could be linked to complementary studies of coastal ocean productivity. There are, as discussed, significant issues regarding the adequacy of the needed data and the availability of the data that currently exist. All are important since all are areas of intense human habitation.

THE ATMOSPHERE-OCEAN SUBSYSTEM

Overview

Models of physical processes in the ocean and atmosphere provide much of our current basis for understanding future climate change. They incorporate the contributions of atmospheric dynamics and adiabatic thermodynamics through the methods of computational fluid dynamics. This approach was initially developed in the late 1940s and early 1950s to provide an objective numerical approach to weather prediction. It is sometimes forgotten that the early development of "supercomputers" at that time was motivated in large part by the need to solve this problem.

The thermal/fluid dynamics approach to the weather system has tended to focus on application of the most efficient and accurate discrete representations of the Eulerian, Navier-Stokes, and thermodynamic equations for a compressible atmosphere on a rotating sphere. Meteorological observations are assimilated into initial fields consistent with the model dynamics; then the prognostic variables (e.g., horizontal winds, temperatures, surface pressure) are specified from these initial fields and integrated forward in time to generate future weather systems. Versions of these weather prediction models were developed in the 1960s to study the "general circulation" of the atmosphere—that is, the physical statistics of weather systems satisfying requirements of momentum and energy conservation. To obtain realistic simulations it was found necessary to begin to include additional energy sources and sinks, particularly by exchanges with the surface and moist atmospheric processes (i.e., moist convective adjustments and precipitation) with the attendant latent heat release and radiative heat inputs.

Incorporating the exchange of energy is an apparently simple but in practice challenging requirement. Models incorporate many complex energy exchange processes, and it is easy to introduce spurious energy sources and sinks either through nonconservative numerical procedures or physical approximations. For example, a model may use a different treatment of latent heat release for precipitation than it does for surface melting and evapotranspiration. Because of the large number of potential sources of inconsistency, it is probably impossible to develop a model that conserves energy perfectly. However, models should be validated to conserve energy to better than 1 W/m^2 and preferably have errors less that 0.1 W/m^2. (The change of atmospheric radiation from doubling CO_2 is about 4 W/m^2.) An atmospheric model coupled to a surface with ocean temperatures prescribed from observations should have radiative imbalance at the top of the atmosphere considerably smaller than this to prevent spurious climate change when coupled to an ocean model. These conservation issues are not unrelated to concerns about numerical drift apparent in coupled atmosphere-ocean GCMs (see Chapters 3 and 4 as well as the subsequent discussion below).

The following discussion focuses attention on three specific critical areas: clouds in atmospheric models, carbon in the ocean, and the problem of linking ocean circulation models with models of atmospheric circulation. We begin with this latter topic since it is crosscutting and ever present.

A Modeling Perspective

Initialization and Coupling: One of the Challenges to Prediction

Coupled ocean-atmosphere GCMs are fundamental to the study of the climate system.[50] Models, by definition, are reduced descriptions of reality and hence incomplete and with error. Missing pieces and small errors can pose difficulties, as indicated above, when models of major subsystems such as the ocean and the atmosphere are coupled. For example, inconsistencies between the submodels can lead to numerical drift when the models are coupled. Another major problem is the initialization of models so that the entire system is in a dynamical and thermodynamical balance—that is, in statistical equilibrium with respect to energy as well as the fluxes of heat, water, and momentum between the various components of the system.[m] Initial imbalances can also cause numerical

[m] There has been progress in this topic of initial conditions and strategies for setting initial conditions in coupled models that are reasonable in light of the perturbation (such as enhanced greenhouse forcing) one is investigating. For climate studies involving ocean-atmosphere-linked systems, one of the most successful initialization techniques developed to date involves integrating each submodel separately to quasi-steady state before coupling. One can then introduce artificial “flux adjustments” to ensure that the linked system is also in quasi-equilibrium and does not drift. Another technique is to use restoring values for data fields to ensure that these fields do not drift away from observations. There remain, however, serious questions about these techniques. In sum, “the reduction and removal of flux adjustments (without significantly degrading the simulation of present-day climate) remain a high priority in the development of coupled models” (Kattenberg et al., 1996, p. 311).

drift. The problem of determining appropriate initial conditions in which fluxes are dynamically and thermodynamically balanced throughout an ocean-atmosphere coupled system is particularly difficult because of the wide range of adjustment times ranging from days to thousands of years. To say that the ocean-atmosphere system is exceedingly stiff is not an overstatement.

As noted in the introduction, the overriding challenge to modeling (and to the USGCRP) is prediction. This challenge is particularly acute when predictive capability is sought on timescales from seasonal to decadal to centennial and where one is confronted with a coupled stiff system like the ocean-atmosphere. In the classical case of prediction—for instance, in weather prediction—one can estimate predictability by evaluating the rate of change of the system from groups of initial states that are close to each other. Relating the differences in these time-evolving states to the errors (differences) in the initial conditions gives a "measure" or at least an insight into the predictive utility of the model. Obviously, if the rate of growth in the difference between the time-evolving states of the system is large relative to the difference in initial conditions, there is some doubt about the predictive capability of the model—or at least one should be concerned. One also has the actual weather versus the predicted weather as a test, and this is far more difficult when studying climate.

There are many variations on this theme. Some methods involve focusing on quantifying well the statistics of the initial conditions and then evaluating the time response under a distribution of initial conditions. For models of the ocean-atmosphere system this careful analysis of the statistical variability in the initial fields is problematic because of a lack of three-dimensional oceanic data fields with statistical information. This is particularly relevant to the question of understanding the physics behind the low-frequency variability of climate and the detection of anthropogenic climate change. These issues must confront longer integration periods than in calculating forecasts for tomorrow's weather or even the seasonal to interannual prediction issues (i.e., El Niño); moreover, on longer timescales (such as decadal to centennial), there is an associated inability (or at least practical difficulty) to test forecasts against what "happens," which is such an integral part of developing and demonstrating prognostic capability. The problem is made even more difficult because of natural climate drifts and changes, whose importance has been recognized throughout this report and elsewhere.[51]

Observations of the ocean-atmosphere system suggest a potential for predictability in the observed broad-area patterns or modes of coherent behavior such as the tropical Pacific ENSO mode, the tropical Atlantic dipole, the North Atlantic Oscillation mode, and others that were discussed in Chapter 4 (see also Chapter 3). The existence of long-lasting, coherent, quasi-periodic modes of behavior suggests that the system may possess extended predictability. On the other hand, this could simply be oceanic damping of atmospheric white noise.[52]

Nevertheless, predictive skills do appear to exist for some of the ocean-atmosphere patterns. Not all modes are simply damped white noise (see again Chapters 3 and 4). The ENSO phenomenon[n] is an example in which both ocean and atmosphere feed back on one another to induce a behavior that appears to be predictable. But as pointed out elsewhere, even if other coupled processes yield long-lasting, large-scale coherent patterns that may be "predictable," there are significant practical issues in developing useful predictions. These include (1) the robustness of the mechanism, (2) the amount of variability involved, and (3) the availability of initial conditions that capture the eventual pattern that is to emerge.[53] These issues and others discussed below are evidence that to use models of complex climate processes usefully one must be able to test thoroughly the coupled dynamics and use extensive ensemble runs where initial conditions are varied. Such tests are computationally intensive and require significant computing resources, *but such tests are essential.*

This short discussion only raises the topic and points to its importance; it is far from a full treatment. Simply stated, the issue(s) of initialization (and flux adjustment) is (are) of central importance and deserve extensive investigation.[54]

Clouds

Another topic that continues to haunt the modeling of the climate system is the role of clouds.[55] It is generally accepted that the net effect of clouds on the radiative balance of the planet is negative[56] and has an average magnitude of about 10 to 20 W/m^2. This balance consists of a short-wave cooling (the albedo effect) of about 40 to 50 W/m^2 and a long-wave warming (the greenhouse effect) of about 30 W/m^2. Unfortunately, the size of the uncertainties in these budgets is large compared to the expected chemical greenhouse forcing. The importance of clouds is best summarized by the recent Working Group 1 report of the IPCC: "The single largest uncertainty in determining the climate sensitivity to either natural or anthropogenic changes are clouds and their effects on radiation and their role in the hydrological cycle."[57]

Handling the physics and/or parameterization of clouds in climate models remains a central difficulty. Recently, it was reported (The Feedback Analysis of GCMs and In Observations [FANGIO])[58] that intercomparison of climate models indicates a decreasing range of model responses to greenhouse forcing from cloud feedback; however, it was noted that this news may not be as positive when examined more closely. Much apparent reduction in uncertainty stems from simply fewer models participating or other reasons that mask the uncertainty.[59] Clouds and their impact on climate *remain the key uncertainty in estimating the sensitivity of Earth's climate to increased greenhouse gases.*

[n] For ENSO prediction there has been a demonstration of success in the most recent event (1997). See Chapter 3.

Cloud modeling is a particularly challenging scientific problem in the climate and global change arena because it involves processes covering a very wide range of space and timescales. For example, from cloud systems extending over thousands of kilometers to cloud droplets and aerosols of microscopic size are all important components of the climate system. The timescales of interest can range from hundreds of years (e.g., future equilibrium climates under a doubled to quadrupled CO_2 concentration) to fractions of a second (e.g., droplet collisions). This is not to say that all cloud microphysics must be included in modeling cloud formation and cloud properties, but the demarcation between what must be included and what can be parameterization and still attain prognostic skill remains highly controversial.

Even the basic issue of the nature of the future cloud feedback is not clear. As the planet warms, it is likely that evaporation will increase, which could yield more clouds, but will these "added" clouds enhance the greenhouse effect or damp it? This question remains open, and it is not clear how it will be answered. As mentioned at the beginning of this subsection, today clouds appear on the basis of observations to have a negative effect on the radiative balance of the planet. Will that be as true in the future?

Given that the current generation of global climate models represent the Earth in terms of gridpoints spaced several hundred miles apart, many observed features on smaller scales, such as individual cloud systems, are not explicitly resolved by the global models. This is at the heart of the spatial problem, but there are interesting approaches being developed that attack this issue. These include efforts to focus on models that include detailed treatment of cloud processes and atmospheric radiation and that resolve atmospheric motions and other processes on a much finer scale than the current global models;[60] to explore this detailed information from the very high resolution limited-area models; to compare these explorations with detailed satellite observations (CERES (Cloud and the Earth's Radiant Energy System) and MODIS (Moderate Resolution Imaging Spectrometer) measurements from Earth Observing System (EOS) AM-1 and EOS PM-1 will likely be particularly useful[61]); and then to develop improved ways to represent small-scale features in global models, despite the fact that the features themselves are not explicitly resolved in the global models.[62]

As previously discussed, cloud radiative feedback is the single most important effect determining the magnitude of possible climate responses to increased greenhouse forcing. DOE's Atmospheric Radiation Measurement (ARM) program[63] was developed to improve predictive capability, particularly as it relates to the cloud-climate feedback. The experimental objective of the ARM program is to characterize empirically the radiative processes in the Earth's atmosphere with improved resolution and accuracy. Two issues are being addressed in ARM: (1) the radiation budget and its spectral dependence and (2) the radiative and other properties of clouds. Understanding cloud properties and how to predict them under expanded greenhouse forcing is critical because cloud properties may very well change as climate changes. Progress here is important, since uncertainty about this important feedback will continue to constrain the utility of coupled climate models for clarifying the role of human activity as a driver of climate change.[64]

Ocean-Atmosphere Carbon System

The natural marine carbon cycle[o] plays an important role in the partitioning of carbon dioxide between the atmosphere and the ocean. The primary controls are the circulation of the ocean and two important biogeochemical processes: the solubility pump and the biological pump, both of which act to create a global mean increase of dissolved inorganic carbon (DIC) with depth and therefore to maintain atmospheric CO_2 at a level considerably lower—about a factor of three—than it would otherwise be.[65] The interplay between the circulation of the oceans and the biogeochemical "pumps" determines the sea surface PCO_2 and hence the primary determinants (with atmospheric PCO_2 and sea surface winds) of the air-sea exchange rates of carbon dioxide.

It is difficult to determine directly from observations the relative strengths of the carbon pumps and ocean circulation on the patterns of air-sea exchange of carbon dioxide and exchange and DIC distribution. Ocean carbon cycle models (see Plate 7), however, provide an attractive means for estimating the relative strengths and potential future patterns and rates of exchange.[66] (See Box 10.5.)

Ocean Circulation

Improvements in ocean-atmosphere models of circulation[68] are central to modeling climate, as are considerations of ocean uptake of carbon dioxide.[69] Central to this improvement is achieving better spatial resolution in atmospheric and oceanic models. In the future we should expect significant improvements in the oceanic component of ocean-atmosphere models as the resolution increases, with increasing availability of computing resources, and as more and more sophisticated subgrid-scale parameterizations are developed and incorporated into these models.[70] This places significant demands not only on the scientific community but also on the available computing resources and is a major issue.

As discussed in the 1994 Special Forum on Global Change Modeling,[71] the atmospheric component of climate models is able to capture significantly better the major storm systems and circulation patterns with models having finer resolu-

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[o] We take the natural carbon cycle to mean the state of the ocean-atmosphere carbon system prior to significant anthropogenic influence on the global carbon budget, usually considered to be the millennia leading up to the nineteenth century, when atmospheric CO_2 concentrations were "steady" at about 280 ppm ± 10 ppm.

BOX 10.5

The IGBP-GAIM Ocean Carbon Model Intercomparison Project (OCMIP[67]) was initiated in 1995 to investigate to what extent predictions from three-dimensional ocean carbon models vary and to understand why. The main goal is to help improve our understanding of the ocean as the major long-term depository of CO_2. The initial effort was put into a comparison of the air-sea CO_2 flux and bomb ^{14}C inventories of four established ocean carbon models (Princeton/GFDL, USA; Max Planck/ Hamburg, Germany; Hadley Centre, United Kingdom; and Institut Pierre Simon Laplace (IPSL), France). This exploratory study found large regional discrepancies between ocean carbon models in estimating CO_2 fluxes and carbon storage (see Plate 8). The issue and approach to resolving these significant regional discrepancies are important.

The next and more difficult stage is to expand the set of three-dimensional ocean carbon models participating in OCMIP and to include models of the important biogeochemical processes in three-dimensional ocean carbon models to evaluate more fully the role of biological processes in the carbon cycle and hence be better positioned to employ coupled ocean-atmosphere models to investigate the potential feedbacks over the next two centuries.

tion. In part this is a reflection of the associated improvement in the representation of major orographic features and in part because of improved ability to represent weather systems, such as the Intertropical Convergence Zone, the Hadley circulation, and other circulation features. In the oceanic component of climate models, ocean current patterns are significantly better represented in models having resolutions finer than about 0.5 to 1 degree in large part because important ocean current systems (e.g., the Gulf Stream and Kuriosho current), ocean variability (including ENSO events), and the thermohaline circulation and other vertical mixing processes can be better represented. Improved resolution in both atmosphere and ocean components of global climate models has also proven to reduce flux imbalance problems (discussed earlier) arising in the coupling of these components. With the increasing parallelism of supercomputers and the availability of massively parallel computers and eventually advanced petaflop machines, a central impediment to gains in model accuracy by improving model resolution is the commitment to make computational resources available. However, as the 1994 forum noted, a concomitant increase in efforts for process studies and diagnosis and analysis of model results also is required. In recent years we have seen a "potential" increase in the availability of computing resources via access to resources at the national laboratories; however, the degree of availability has been unclear. The necessary "concomitant" increase in resources for process studies, diagnosis, and analysis has been even more difficult to realize.

The coming decade will be particularly important for ocean circulation in the context of global change. The World Ocean Circulation Experiment (WOCE)[72] will be executing its Analysis, Modeling, and Synthesis Phase coupled with the maturing of the exciting ocean topography data that are flowing from the TOPEX-Poseidon mission. A central theme will be on the match between oceanic models and the observed data. Key questions, such as how well ocean models capture the inferred heat flux or tracer distributions (see below), are central to the use of these models in climate and other global change studies. A particularly exciting development is the potential for assimilating ocean topography data into ocean general circulation models. The intercomparison of ocean models through the efforts of the World Climate Research Program[73] and the International Geosphere-Biosphere Programme[74] and the direct comparison of models with data must be a continuous theme for the future. The latter effort, comparing models with data, as the direct path for model rejection and model improvement is particularly important. It is, in a sense, the true reason for WOCE and Joint Global Ocean Flux Study (JGOFS)[75]; the latter has been particularly focused on the various biogeochemical pumps at work in the ocean carbon system.

Biogeochemical Pumps

The "biogeochemical pump," which transfers CO_2 in the surface ocean to other physical, chemical, and biological components, is actually three pumps: the solubility pump and the biological pump, which is itself two pumps—the organic matter pump and the calcium carbonate pump.

The solubility pump maintains a vertical DIC gradient because cold waters, which originate in high latitudes and fill up the deep ocean, can hold more DIC than warm waters at equilibrium with a fixed atmospheric pCO_2, a result of the higher solubility and dissociation of CO_2 (into carbonate and bicarbonate ions) in cold water. The vertical DIC gradient depends not only on the vertical temperature gradient but also on the degree to which surface waters equilibrate with the atmosphere before sinking. Unlike most gases, the equilibration of surface water CO_2 with the atmosphere takes about one year, and therefore the strength of the solubility pump may depend critically on the kinetics of air-sea gas exchange. It is worthwhile to note that important uncertainty remains about the basic chemical (apparent) disassociation coefficients that must be removed.

The biological pump consists, as mentioned, of two separate pumps—that of organic matter and calcium carbonate. The organic matter pump affects the DIC (and dissolved organic carbon, DOC) distribution through the photosynthetic formation of organic carbon in surface waters and the sinking and subsequent remineralization of this organic matter deeper in the water column. The carbonate pump affects the DIC distribution though the biogenic precipitation of calcium carbonate in surface waters and the subsequent sinking and dissolution of this material deeper in the water column. These two pumps also affect the alkalinity of seawater (and hence link to the solubility pump) through the nitrate and dissolved calcium distributions.

It has been pointed out by a number of modeling studies that if there were no biological pump the preindustrial atmospheric CO_2 concentration would have been 450 ppm instead of 280 ppm. Any complete model of the natural ocean carbon cycle should therefore include the biological pump; however, most recent assessments of the oceanic uptake of anthropogenic CO_2 have assumed that the biological pump would not be affected by climate change and have therefore only modeled the physical solubility pump.[76] A recent exception is a coupled ocean-atmosphere model used to show that including a simple parameterization of the biological pump significantly altered the calculations of total uptake of CO_2 over timescales of 70 to 140 years.[77] This result demonstrates the importance of including simple models of the biological pump in ocean carbon cycle models.

Models of the organic matter pump need to simulate the net biogenic uptake of dissolved inorganic carbon in surface waters (new production) and the net remineralization in the aphotic zone of the organic carbon. Models of varying complexity and assumptions are rapidly being developed, and the JGOFS datasets will no doubt provoke the formulation of more realistic biological models. Simulating new production is complicated by the many factors that govern the rates of photosynthesis, such as light and the availability of a variety of nutrients (nitrate, ammonia, phosphate, silicate, and possibly iron), both of which depend on the physical environment, such as mixed-layer depth and the flow field, particularly vertical velocity. A simplification is possible, however, if the organic matter pump treats phosphorus (or nitrogen) and carbon in a grossly similar fashion, differing only in the relatively constant Redfield ratios. In that event, simulation of the organic matter pump is tantamount to simulating the distributions of nitrate or phosphate. There are deviations from an invariant Redfield stoichiometry, but these deviations may at least initially be regarded as relatively minor. The topic is important and needs research. Current nutrient restoring or other empirical approaches (see below) are useful and need investigation, but for prognostic calculations a more process-oriented approach is necessary. A problem remains in defining a minimum complexity model that can represent the preindustrial pump and, by extension, the present-day organic pump. Candidate models range from those in which new biological production (and therefore the export flux to the deep ocean) is treated implicitly by relaxing surface nutrients to observed values[78] to multicomponent ecosystem models[79] in which the biological processes controlling the export flux are modeled explicitly.[80]

The principal advantage of the nutrient-restoring approach is that it provides a data-constrained and circulation-coherent estimate of an important but poorly constrained quantity on large scales: new production. Given that the new production so estimated will depend critically on the modeled ocean circulation field, it is important to have several estimates from different circulation models to produce confidence intervals for predicted global and regional new production. We note that the nutrient-restoring algorithms are relatively easy to install in circulation codes. A second advantage of this approach is that it facilitates a focus on aphotic zone remineralization. Modeling studies suggest that the aphotic zone nutrient and oxygen distributions are highly sensitive to the type of organic matter (dissolved or sinking particulate) exported from the photic zone, as well as the lifetime of that organic matter. Thus, improved estimates of aphotic zone remineralization can be coherently linked and/or compared using the nutrient-restoring method.

There are two main disadvantages of the nutrient-restoring approach. First, small mismatches between the observed and simulated ocean circulation field, particularly with regard to vertical motion, can lead to erroneous and unreasonably patchy estimates of new production. This difficulty can be minimized, as indicated above, by running the nutrient-restoring algorithm in several different circulation codes. A second disadvantage of the nutrient-restoring approach is that it is of little use for predicting future variations in the natural marine carbon cycle, such as might be expected if ocean circulation changes. The nutrient-restoring method is still a useful check and a reasonable first step in addressing the organic pump but what is needed are more process-oriented marine ecosystem models.

Beyond the check from the nutrient-restoring method, evaluation of such process-based organic pump models (i.e., predicted new production fields) becomes a crucial issue. One promising approach is to simulate dissolved oxygen, linking the source/sink terms for nutrients to those for oxygen using a Redfield ratio, and comparing the model-predicted oxygen with observations. Until recently, such a model evaluation was only possible in the deep sea, outside the depth range of seasonal variability. Now, however, seasonal surface analyses are available,[81] revealing summertime supersaturation and wintertime undersaturation (on average) patterns that largely reflect summertime new production and wintertime entrainment of deeper oxygen-depleted waters. Such models tested against in situ data take on even greater importance when complemented by ocean color observations from satellite. In sum, prognostic ecosystems are needed for the organic pump, but it will be important to cross-check these models with the nutrient-restoring method, and this cross-check can now include seasonal considerations.

Simulating the calcium carbonate pump with a process-oriented model presents another level of complexity beyond simulating the organic matter pump: the distribution of particular phytoplankton species (mainly coccolithophorids) must be simulated. Fortunately, the calcium carbonate pump contributes relatively little to the vertical DIC gradient compared to the organic matter and solubility pumps. The importance of this pump needs careful evaluation and its past (paleo) role in the carbon cycle needs to be considered. It is not yet completely clear how to treat the $CaCO_3$ cycle in ocean carbon cycle models. One possibility is to use a restoring technique similar to the nutrient cycle. This is more difficult for

$CaCO_3$ because the amount and quality of alkalinity observations are not as high as for nutrients. Yet another approach is to restore surface silicate to observations, determining net biogenic silica formation. In regions of low silica production, one can assume that coccolithophorids dominate production. In such regions the $CaCO_3$ uptake can be linked to new production using a fixed ratio. Another possibility is to assume that coccolithophorids dominate in low-productivity regions. Finally, it may be best to evaluate more carefully the role of the individual pumps as one means of focusing on the most important issues.

In principle, it is possible to evaluate models of the separate pumps (even though they are quasi-linked). For instance, removing the biological pump and anthropogenic contamination from the DIC distribution can test models of the solubility pump. The organic matter pump can be removed using the apparent oxygen utilization and an estimate of the respiration quotient. Alkalinity, corrected for nitrate, can be used to eliminate the calcium carbonate pump. The anthropogenic component can be eliminated using related techniques or by incorporating transient tracers that reveal age information.[82]

In early IPCC assessments of the effects of increased atmospheric CO_2 on climate change, the role of the marine biota was largely ignored.[83] This was based on the understanding that marine algal growth is limited by nitrate or other nutrients but not, as mentioned above, by CO_2. There would therefore be no CO_2 fertilization effect as has been suggested for terrestrial plants, and unless there was a large change in the nutrient supply to the upper ocean because of a climate-induced shift in circulation, no extra anthropogenic CO_2 could be sequestered to the deep ocean by the biological pump.[84] Since 1990, JGOFS has been studying the biological pump, and this effort and other research work have suggested a number of possible ways in which the biological pump might be affected by climate change over a 200-year timescale.[85] The main conclusion was that because of the complexity of biological systems it was not yet possible to say whether some of the likely feedbacks would be positive or negative. However, it is clear that an understanding of some of the scientific issues could be greatly assisted by an integrated and focused cross-disciplinary modeling program. It is difficult to determine directly from observations the relative strengths of the carbon pumps and ocean circulation on the patterns of air-sea exchange of carbon dioxide and DIC distribution. Ocean carbon cycle models, however, provide an attractive means for estimating the relative strengths as well as potential future patterns and rates of exchange.

Ocean Tracers: A Diagnostic Tool for Ocean Carbon Cycle Models

Since ocean circulation plays a key role in the natural and anthropogenic marine carbon cycle, we need to quantify its current effect to understand better its potential future role. The biological pumps also need to be understood and evaluated in the context of the general circulation of the ocean and the ocean carbon cycle. Tracers provide information about the types of ocean circulation relevant for the marine carbon cycle, and many give insight into aspects of the biological pump (in fact, the nutrient-restoring algorithm is a purely tracer-driven approach). Fortunately, tracers such as radiocarbon, both natural and bomb produced, and chlorofluorocarbons as well as DIC and DOC have been extensively measured in the ocean (most recently and extensively in the WOCE and JGOFS programs). The transient tracers are particularly attractive because they have atmospheric histories similar (though not identical) to anthropogenic CO_2 and they have equilibration times in surface waters (~1 month for fluorocarbons and 10 years for ^{14}C) that bracket the equilibration time for CO_2 (~1 year). Natural radiocarbon is most useful for establishing the veracity of model representations of the circulation of abyssal waters. This circulation currently does not play a large role in CO_2 uptake but will likely become very important over the next few hundred years. The following brief discussion focuses on carbon 14 and the fluorocarbons as example tracers.

Atoms of ^{14}C are produced naturally when nitrogen is bombarded with cosmic radiation in the upper atmosphere. This ^{14}C rapidly attaches to molecules of CO_2, enters the ocean through air-sea gas exchange, and subsequently decays (with a half-life of 5,730 years), mostly in the deep ocean. Gradients of ^{14}C result, both vertically and horizontally, that depend on how long waters have been isolated from the ocean's surface. Beginning with the atmospheric nuclear weapons tests during the 1950s, the ^{14}C content of the atmosphere increased sharply. At its peak in 1963, atmospheric ^{14}C was nearly double that of preindustrial times. Subsequently, atmospheric ^{14}C has declined, following implementation of international treaties banning atmospheric weapons tests. Today atmospheric ^{14}C is only about 10 percent greater than during preindustrial times. By carefully separating out the nuclear component through correlations with other ocean tracers, oceanographers have been able to use the bomb ^{14}C signal in the ocean as a primary dataset with which to evaluate ocean circulation models.[86]

Many new high-precision measurements of oceanic ^{14}C are now becoming available from samples collected during WOCE and JGOFS. Because of its much finer resolution, validations using both natural and bomb ^{14}C will benefit from this dataset. Due to the weak flows characteristic of most of the deep ocean, it is not possible to measure directly much of the ocean's deep circulation. One can use natural ^{14}C, however, as a type of clock for deep-ocean circulation. An additional interest for the bomb component concerns its use as an analog for anthropogenic CO_2. Ocean carbon cycle model comparisons confirm that the distribution of anthropogenic CO_2 resembles much more closely the bomb ^{14}C during WOCE than during the earlier Geochemical Ocean Sections Study (GEOSECS[87]). Boundary conditions have changed considerably since the latter campaign, which originated only 10 years after the 1963 peak in atmospheric ^{14}C. An important test is to compare ocean model results to both the GEOSECS and WOCE, focusing on site-specific changes in ^{14}C (where possible). This time increment can be used to remove uncertainties associated with estimating prenuclear ^{14}C from the observations, and it can also provide a tracer that more closely resembles anthropogenic CO_2.

An example of the utility of natural radiocarbon for evaluating the deep circulation fields of ocean models can be seen by considering Plate 8, which contains radiocarbon results from the initial phase of OCMIP. Along the Western Atlantic GEOSECS section, the observations reveal that the basin north of the equator is filled with waters penetrating from the north, which are at most 500 years old, a signature of North Atlantic deep water (NADW). In the Geophysical Fluid Dynamics Laboratory model, no younger waters from the north penetrate deeper than 2,500 m. In the Hadley Center model, younger waters fill the basin, but the structure of the ^{14}C distribution is rather different from observations; apparently, vertical infiltration of ^{14}C is excessive. In the Max Planck Institute model, young waters also fill the North Atlantic basin, although here the structure of the north-south ^{14}C gradient is closer to that observed, despite evidence of somewhat inadequate infiltration of older waters from the south along the bottom. In the Institut Pierre Simon Laplace model, young ^{14}C waters fill the deep northern basin, but southward penetration of the youngest waters (north of 30°N) is not deep enough. On the other hand, this model seems to most closely match observations, which show a tongue of young ^{14}C water extending from the north at around 2,500 m (the NADW) and overlying intermediate waters that move northward from the south. Analogous natural ^{14}C sections for the Pacific reveal that all four models predict rates for the northward penetration of bottom waters, which are consistently too slow.[88]

These penetration issues are important to past, present, and future rates of uptake of carbon dioxide and are tied to the ocean role in longer-term climate change. They need to be better understood.

In addition to the challenge of matching ^{14}C, models need to be compared to direct anthropogenic CO_2 data that are based on measured CO_2 system variables and tracer ages along isopycnal surfaces. More generally, full natural carbon cycle simulations should be validated with available datasets for dissolved inorganic carbon, oxygen, and alkalinity. Gridded seasonal maps of Delta-pCO_2 (pCO_2(ocean) - pCO2(atmosphere)) have recently become available for the North Atlantic[89] and will be used to constrain CO_2 air-sea fluxes. New U.S. efforts are beginning to provide maps for the entire Atlantic Ocean and the North Pacific, and international efforts have begun to construct a global Delta-pCO_2 dataset. Finally, chlorofluorocarbons (CFCs) are excellent tracers of ocean circulation for several reasons. First, they readily equilibrate in surface waters, so that the "preformed" CFC concentration is easily estimated from the well-known atmospheric CFC concentrations and the CFC solubility in seawater. Second, CFCs are entirely anthropogenic, having no natural "contamination," and are essentially inert in seawater. Third, the ratio of CFC-11 to CFC-12 in the atmosphere has, until recently, varied coherently, so that this ratio in seawater can be used in many cases to estimate the age of water parcels; moreover, accurate CFC measurements can now be made relatively easily, and as a result nearly 100,000 measurements for CFCs now exist. Most importantly, the distributions of CFCs have yielded insight into the many circulation processes relevant to the uptake of anthropogenic tracers, such as ventilation of the thermocline, intermediate and deep-water formation, ventilation of the interior deep ocean through exchange with deep western boundary currents, and evaluation of oceanic general circulation models in general.[90]

Despite some uncertainty associated with this tracer-based approach, continued efforts with newly released WOCE-JGOFS data will eventually provide an excellent global database with which to evaluate three-dimensional ocean carbon cycle models.

Research Priorities

First and foremost, long-term consistent data are needed to support modeling investigations.[p] The various reanalysis projects are immensely valuable and should be extended to include coherent boundary forcing fields such as surface temperatures, wind stress, and sea-ice extent as well as independent estimates of precipitation and evaporation. As mentioned earlier, a central activity for the coming decade is to compare models with data; for the oceans this means careful comparison of models with WOCE and JGOFS ocean data fields.

Along with data from the present and recent past (the past 100 years), it is important to establish highly credible global climate-relevant data fields for the past 1,000 years along with lower-frequency data for the past 6,000 years. Given the scarcity of geographically specific detailed climate data for the past 1,000 years and the importance of climate variability over timescales of a millennium, it is important that extensive climate system models be carefully intercompared. This intercomparison should take place in models not restricted to the ocean-atmosphere system but should also include the terrestrial biosphere, although perhaps initially in a somewhat passive mode.

Initialization of coupled models for use in investigating climate variability and anthropogenic change has been and remains an important research topic.

[p] "It is important to understand how natural climate variations interact with human-induced changes. There are several issues here. First, as already noted, there needs to be a continuing high quality global climate monitoring system to better establish the changing state of the climate. Then we must know how the climate system varies in the absence of anthropogenic forcing. For example, a better understanding of El Niño should include factors that determine its intensity and frequency. El Niño may be affected by anthropogenic climate change. Through better observations, paleoreconstructions and improved knowledge and understanding of natural variability, it will be possible to detect the anthropogenic climate signal with greater confidence" (McBean et al.,1995, p. 527).

Success in initialization will be essential if geographical resolution is to be improved. Initialization focuses attention on the evaluation of model results and the intercomparison of models. As we resolve finer-scale issues, such as ocean eddies, these accomplishments will raise afresh the issues of coupling shock and model initialization. In such investigations, hybrid schemes should be considered in which low-resolution atmospheric models might be used in the initial stage of coupling. The questions of coupling and initialization are so closely connected with the long-term prediction problem of climate and of CO_2 uptake by the oceans (and the terrestrial biosphere) that they must be central in future modeling work.

There are large differences in GCMs with respect to the scales of cloud microphysics and the treatment of these processes. There also tends to be a very real difference in focus between those models addressing the climate system at the large scale and those focused on small-scale processes as they occur in reality. To clarify the role of clouds in models, a hierarchy of models and observations needs to be used, and there should be greater emphasis on studies to isolate specific cloud processes. Finally, it would be useful to have a benchmark set of cloud and radiation diagnostics to be used to analyze feedbacks and compare models with observations.

The oceans are very energetic on spatial scales of 10 to 100 km, yet these motions are not resolved in the current generation of global climate models. A major unsolved problem in oceanography is to determine the effects of these unresolved mesoscale ocean eddies on large-scale circulation and climate.

The WOCE and JGOFS datasets of carbon and CFCs in combination with the ocean topography from the Ocean Topography Experiment (TOPEX/Poseidon)[91] and the current and next generation of satellite ocean color products,[92] as well as a number of existing seasonal, global-scale syntheses of nutrients, dissolved oxygen, surface carbon dioxide, and chlorophyll, present an unprecedented opportunity for evaluating models of the marine carbon cycle and extending our knowledge of its current state and potential future states. This is, as stated repeatedly, a central effort for the next decade.

THE ATMOSPHERIC PHYSICAL-CHEMICAL SUBSYSTEM

Overview

As we have noted throughout this report, important future changes of the Earth system will probably result, in part, from increasing atmospheric concentrations of greenhouse gases such as carbon dioxide, CFCs, methane, and nitrous oxide. These substances have biological, industrial, and other anthropogenic sources. In addition to their direct radiative effect, some of these gases undergo atmospheric chemical and photochemical transformations that alter the natural balance of other atmospheric gases. An important example is ozone, whose changes in both the stratosphere and the troposphere are a source of serious global concern (see Chapter 5).

In reflecting about challenges in modeling the interaction of the physics and the chemistry of the atmosphere it is important to review the extraordinary successes that have been achieved and to recall the scientific and political challenges that faced the planet just a few decades ago.

The Earth's stratosphere contains a thin but crucial layer of ozone that filters out many damaging forms of solar radiation and makes life as we know it possible on the Earth's surface. Beginning in the 1970s, scientists became concerned that certain human-produced chemicals, known as CFCs, could diminish the stratospheric ozone layer.

In the 1980s atmospheric concentrations of CFCs continued to increase, and decreases in stratospheric ozone began to be detected. Stratospheric ozone concentrations over Antarctica plummeted at a remarkable rate during the Antarctic springtime—a phenomenon now referred to as the Antarctic ozone hole. Meanwhile, atmospheric scientists continued working to refine their models of ozone depletion, which had not predicted losses nearly as large as those observed over Antarctica. As a result of a crosscutting scientific effort, including theory, modeling, and observations, a sound scientific basis for the protection of stratospheric ozone was established. In response to the scientific findings, an international agreement was reached to halt production of the most destructive ozone-depleting chemicals. The decisive response of the world community to the stratospheric ozone threat was a tribute to a combined international scientific and policy-making effort.

Advanced three-dimensional atmospheric models were developed to study the interaction of chemistry, dynamics, and radiation in the stratosphere. These extensive calculations were necessary for evaluating the simpler models used in the policy assessment studies as well as for understanding the climatic impact of the Antarctic ozone hole.

Many questions are still unanswered about the future of stratospheric ozone. Will an ozone hole like the one over Antarctica develop over the northern hemisphere in the coming years? How will greenhouse gas-induced climate change interact with stratospheric ozone chemistry? These and other problems, such as the emergence of a global tropospheric ozone problem (see Chapter 5), involving the physics and chemistry of the atmosphere will challenge the scientific community for decades into the future.[93]

A Modeling Perspective

The goal is a completely interactive simulation of the dynamical, radiative, and chemical processes in the atmosphere. Such a model will be essential in future studies of tropospheric trace constituents such as nitrogen oxides, ozone, and sulfate aerosols. Nitrogen oxides are believed to control the production and destruction of tropospheric ozone, which controls the chemical reactivity of the lower atmosphere and is itself a significant greenhouse gas. Tropospheric sulfate aerosols, on the other hand, are believed to significantly affect the Earth's radiation budget by scattering solar radiation.

Models that incorporate atmospheric chemical processes provide the basis for much of our current understanding in such critical problem areas as acid rain, photochemical smog production in the troposphere, and depletion of the ozone layer in the stratosphere.[94] These formidable problems require that models include chemical, dynamical, and radiative processes, which through their mutual interactions determine the circulation, thermal structure, and distribution of constituents in the atmosphere. That is, the problems require a coupling of the physics and chemistry of the atmosphere. Furthermore, the models must be applicable on a variety of spatial (regional to global) and temporal (days to decades) scales.[95] Fortunately, there have been advances in three-dimensional modeling of the chemistry of both the stratosphere and the troposphere, including modeling the tropospheric distribution of aerosols.[96]

Until relatively recently, atmospheric chemistry studies have often relied on two-dimensional (latitude and altitude) models.[97] These models solve the zonally averaged momentum, thermodynamic, and mass continuity equations and include a detailed treatment of chemistry and radiative processes. Because of the demanding computational requirements, many two-dimensional models group related constituents into "families" to avoid explicit integration of a mass continuity equation for each individual chemical species (not unlike the grouping that occurs in ecosystem models). A major problem with two-dimensional models has been the necessity to include the effects of horizontal transport by zonally asymmetric motions (waves or eddies) by means of eddy diffusion terms analogous to the approach adopted for vertical transport in the one-dimensional models. As a consequence, these models do not correctly represent the interactive behavior of the chemical, radiative, and dynamical processes. Despite their shortcomings, the models have provided significant insight into atmospheric chemical processes through incorporation of horizontal motions. They will also continue to provide the basis for ozone assessment studies well into the next decade, until significant progress is made in developing three-dimensional models and acquiring and making available the essential, more powerful computing resources, since it is not just the computational cost of the fluid dynamic equations but the chemistry equations as well (which are often the most computationally expensive step).

Most effort in three-dimensional atmospheric chemistry models over the past decade has been in the use of transport models in the analysis of certain chemically active species (e.g., long-lived gases such as N_2O or the CFCs). In part, the purpose of these studies was not to improve our understanding of the chemistry of the atmosphere but rather to improve the transport formulation associated with GCMs and, in association with this improvement, for understanding sources and sinks of carbon dioxide.[98] More recently, attempts have been made to develop more chemically intensive three-dimensional global models. Although efforts to include chemistry in a three-dimensional model date back at least two decades, progress has been relatively slow due to the enormous computational requirements for treating the fluid dynamic equations alone. The additional burden imposed by incorporating detailed chemistry into a comprehensive GCM has made long-term simulations and transient experiments with existing computing resources impractical. Current three-dimensional atmospheric chemistry models that focus on the stratosphere seek a compromise solution by combinations of expedients: using coarse resolution (both vertical and horizontal dimensions); incorporating constituents by families (similar to the practice used in most two-dimensional models); omitting or simplifying parameterizations for tropospheric physical processes; or conducting "off-line" transport simulations in which previously calculated wind and temperature fields are used as known input to a series of mass continuity equations including chemical source/sink terms. This last approach renders the problem tractable and has produced much progress toward understanding the transport of chemically reacting species in the atmosphere. The corresponding disadvantage is the lack of interactive feedback between the evolving species, distributions, and the atmospheric circulation.

As attention is turned toward the troposphere, the experimental strategy simply cannot adopt the stratospheric simplifications. The uneven distribution of emission sources at the surface of the Earth and the role of meteorological processes at various scales must be addressed directly. Fine-scaled three-dimensional models of chemically active trace gases in the troposphere are needed, which should resolve transport processes at the highest-possible resolution. These models should be designed to simulate the chemistry and transport of atmospheric tracers on global and regional scales with accurate parameterizations of subscale processes that affect the chemical composition of the troposphere. It is therefore necessary to pursue an ambitious long-term perspective to develop comprehensive models of the troposphere system, including chemical, dynamical, radiative, and eventually biological components. The development of such models and their integration in even more complex Earth system models will require stable long-term support for interdisciplinary research teams to clarify processes and develop the needed in situ datasets, including improved estimates of past and present trace gas emissions. A large effort will have to be devoted to studies of various individual processes affecting the interplay of atmospheric chemistry and physics on global and regional scales. These models will require significantly advanced computing machinery that is currently simply not available to the USGCRP. There are no shortcuts with respect to the needed process studies, the required in situ data, the essential computing power, and organized support for model development and evaluation.

Efforts to develop a fully coupled atmosphere-ocean GCM with linked atmospheric chemistry and physics are still in their infancy. Fortunately, there has been exciting progress in the past decade. Two examples bear special mention:

the National Center for Atmospheric Research (NCAR) IMAGES model and the chemical transport models coupled to the NCAR CCM2.[99]

NCAR IMAGES Model

The Intermediate Model for Global and Annual Evolution of Species (IMAGES) has been developed to reproduce the three-dimensional distribution of chemically active trace gases in the troposphere and to study the relative contributions of chemistry, advective and convective transport, surface emission, and deposition in the global budget of these species. The model extends from the surface to the 50-mbar pressure level, including 24 unequally spaced levels in the vertical and a horizontal resolution of 5° in latitude and longitude. It deals with species belonging to the oxygen family (ozone and oxygen atoms), the nitrogen family (NO, NO_2, NO_3, N_2O_5, HNO_3, peroxyacetylnitrate), the hydrogen family (OH, HO_2, H_2O_2), carbon oxides (CO, CO_2), hydrocarbons (CH_4, isoprene), and several intermediate products of hydrocarbon degradation. Chemical and photochemical reactions required to simulate the reactions affecting these species are taken into account. To ensure computing efficiency, the photodissociation coefficients are provided from a look-up table as a function of altitude, ozone column abundance, solar zenith angle, and surface albedo. Diurnal variations of photochemical processes are either explicitly simulated or parameterized through a correction in the reaction rates.

The transport of trace constituents is formulated by the semi-Lagrangian transport model. What makes the model "intermediate" is that the transport is driven by observed monthly mean winds (as opposed to winds provided every few hours). The effect of wind variability over a month is expressed through an eddy diffusion formulation with the diffusivity derived from the observed wind variance. Convection is assumed to take place in cumulonimbus-type clouds whose spatial and temporal distribution is provided by climatology.

In the present version of the model the geographical distributions of trace gas surface emission and deposition on the global scale are taken from literature estimates. Biogenic sources, including emissions from biomass burning, foliage, and soil, are established for each month of the year on the basis of a world ecosystem database. Anthropogenic sources, including fossil fuel burning, industrial processes, and waste disposal, are established on the basis of economic statistics.

Chemical Transport Models Coupled to the NCAR CCM2

The chemical transport model coupled to the NCAR Community Climate Model (CCM2) is very similar to IMAGES for the surface sources of trace constituents, chemical reactions, and surface deposition. Transport is also expressed through a semi-Lagrangian formulation. There are, however, important differences from IMAGES. First, the model extends up to the pressure level of 2 mb and therefore includes a large part of the stratosphere. Second, the horizontal resolution corresponds to a spectral model with 42 waves in the meridional and zonal directions, respectively, with triangular truncation (T42). Versions of the model at lower resolution are also available. Third, the winds are provided by CCM2 at relatively short intervals (e.g., six hours). The model can be run either in an online mode (synchronously with the dynamical model) or an offline mode (using the winds previously calculated and stored). Tests are currently performed to validate the offline approach and determine the most appropriate way by which dynamical variables (including the information on vertical convection) should be transferred from the GCM to the transport model. The model will also be run with analyzed winds (e.g., from the European Centre for Medium-Range Weather Forecasts), especially when model results will be compared to observations at specific sites.

One of the major challenges is incorporating heterogeneous reactions into models. As discussed in Chapter 5, we now know that during Antarctic springtime reactions on the surface of polar stratospheric cloud particles are instrumental in the destruction of polar ozone. Similar heterogeneous reactions on sulfate aerosol particles at middle latitudes are also possible. There is also concern about enhancements of the stratospheric aerosol burden by large volcanic injection events (e.g., El Chichon) and the release of aerosols through industrial activity and their diffusion into the stratosphere. Although a substantial database on aerosols exists (both satellite and ground-based data), global atmospheric chemistry models typically do not include aerosol effects.

In addition to chemistry issues, a number of shortcomings in current models are related to dynamical processes and thereby affect the ability of the models to predict the distribution of chemically reactive species. For example, global models typically do not simulate those equatorial wave modes (Kelvin and Rossby gravity waves) that are thought to force the semiannual and quasi-biennial oscillations in the stratosphere. This inadequacy of the models is either a result of insufficient resolution or failure to include tropospheric convective processes believed to be the source of these waves. Some atmospheric chemistry models (notably two-dimensional models) have attempted to include these effects by ad hoc methods.

Perhaps an even more important deficiency in models used to study atmospheric chemistry is the failure to include, or to treat adequately, cloud processes and the hydrological cycle. This fault results from both inadequacy of computational resources and incomplete understanding of the hydrological cycle. The consequence of this deficiency is typically a poor simulation of the observed water distribution, and this implies an inadequate treatment of gas sources and sinks, particularly in terrestrial systems.

In sum, there is an emerging consensus that both two- and three-dimensional atmospheric chemistry models will require significantly higher resolution than is now common. Furthermore, there is a need for long-term simulations (tens of years) to examine the interannual variability exhibited by the models and the degree to which that variability is consistent with observed statistics. These considerations pose significant computing resource demands if progress is to be achieved. In addition, there are many gaps in our fundamental understanding of chemical and dynamical processes (and radiative processes to a lesser extent), which inhibit progress in modeling atmospheric chemistry.

Research Priorities

Further progress in modeling the interplay between the physics and chemistry of the atmosphere requires a better knowledge in five key areas:

1. *Surface sources and sinks of trace gases*, in particular exchanges of terrestrial ecosystems with the atmosphere and exchanges between the surface ocean and the atmosphere. Understanding will be advanced partly by systematic observations of different terrestrial ecosystems and surface marine ecosystems under variable meteorological conditions and by the development of ecosystem and surface models that will provide parameterizations of these exchanges.
   - Global empirical models of surface emissions are necessary to extrapolate and interpolate individual measurements provided in different environments under different conditions. These models will be based on empirical relationships accounting for the variation in emissions with climate parameters such as temperature, solar radiation, and soil moisture. In addition, there is a need to improve our understanding of historical as well as present emissions.
   - Models of detailed biological mechanisms in terrestrial and oceanic systems associated with trace gas emissions in soil, oceans, etc., need to be developed. The processes to be considered will range from the leaf of a tree to an entire ecosystem.
   - Models and associated in situ data of physical processes, surface exchanges, and transport in the boundary and surface layers that describe the transfer of key chemical species between the ocean or land surfaces and the atmosphere.
   - An extensive and long-term system of in situ atmospheric observations of key chemical species (e.g., carbon dioxide) from a suite of towers (e.g., AmeriFlux,[100] EUROFLUX,[101] and JapanNet[102]) is needed, together with long-duration aircraft and oceanic buoy arrays.
2. *Chemical models* with a detailed set of reactions, in which transport is ignored, need to be developed. These models will describe the complex relationship between hydrogen, nitrogen, and oxygen species as well as

hydrocarbons and other organic species and will be used to establish simplified chemical schemes that will be implemented in chemical/transport models.

3. *Transport models* coupled to GCMs, with detailed representation of physical processes, including cloud formation and boundary layer transport, are required to simulate how advection, turbulence, and convection affect the chemical composition of the atmosphere. Several approaches can be used, including Eulerian and Lagrangian formulations. These models will be used with minimum chemistry to simulate the global distribution and variability of long-lived species (e.g., greenhouse gases) and with more detailed chemistry to explore the role of meteorological processes in determining the spatial distribution and temporal variability of short-lived species. In this second case the importance of continental pollution on the remote troposphere and on the oxidizing capacity of the atmosphere needs further study.
4. *Hydrological processes and energy exchange*, especially processes involving clouds, surface exchanges, and their interactions with radiation, are crucially important research problems. Determining feedbacks between the land surface and other elements of the climate system will require careful attention to the treatments of evapotranspiration, soil moisture storage, and runoff. These topics have arisen several times in this chapter. All of these occur on spatial scales that are small compared to the model meshes, so the question of scaling must be addressed. These improvements must be paralleled by the acquisition of global datasets for validation of these treatments. Validation of models against global and regional requirements for energy conservation is especially important in this regard.

   In a similar vein, to simulate the effects of clouds on chemical constituents and to investigate the mechanisms involved in wet removal of atmospheric constituents, models should be developed to account for the following processes: cloud convection, which provides an efficient mechanism for vertical transport in the troposphere; meteorological transport through the boundary and surface mixed layer; aqueous transformations of species in clouds; and precipitation of trace gases and wet deposition. This may require the development of subgrid-scale convection routines in the models, including the planetary boundary layer, with moist processes and treatment of cloud and precipitation physics to provide radiatively important parameters, such as cloud liquid water and drop size distributions.

   Finally, improvements are needed in models of aerosols and how they affect homogeneous chemistry and the hydrological cycle. This coupling of aerosols with both the energy and the water cycles as well as with the chemistry components of the system is of increasing importance. In addition, advances are needed in models to examine the effects of chemical changes on climate processes such as convection changes through heating the midtroposphere.

5. *Models of the middle atmosphere* are used in relation with the ozone budget. Many studies are based on two-dimensional models that include a relatively detailed chemical scheme as well as a radiative code that takes into account the important coupling between radiative (thermodynamic) and chemical processes. Three-dimensional models need to be improved and applied to the middle atmosphere. These models will be able to reproduce explicitly the propagation of planetary waves and simulate their effects on the meridional transport of trace gases such as ozone. These models are also needed to study the dynamical and chemical mechanisms involved in the formation and dissipation of the ozone hole over Antarctica. Models of the stratosphere should include the effects of aerosols and polar stratospheric clouds on chemical budgets.

THE HUMAN LINKAGE TO THE EARTH SYSTEM

Human processes are critically linked to the Earth system as contributing causes of global change, as determinants of impacts, and through responses. Representing these linkages poses perhaps the greatest challenge in modeling the Earth system. But understanding them is essential to understanding the behavior of the whole system and to providing useful advice to inform policy and response. Significant progress has been made, but formidable challenges remain (see Chapter 7).[103]

Human activities have altered the Earth system at all spatial scales, and many such influences are accelerating. Fossil fuels and chemical fertilizers are major influences as is the human transformation of much of the Earth's surface over the past 300 years. Land use change illustrates the potential complexity of linkages between human activity and major nonhuman subsystems of the Earth system. The terrestrial biosphere is fundamentally modified by land clearing for agriculture, industrialization, and urbanization and by forest and rangeland management practices. These changes affect the atmosphere through altered physical properties such as albedo and roughness and consequently an altered energy balance over the more intensively managed parts of the land surface, as well as through changed fluxes of H_2O, CO_2, CH_4, and other trace gases between soils, vegetation, and the atmosphere. Changed land use also greatly alters the fluxes of carbon, nutrients, and inorganic sediments into river systems and consequently into many oceanic coastal zones.

The response of the total Earth system to these changes in anthropogenic forcing is currently not known. Sensitivity studies with altered land cover distributions in GCMs have shown that unrealistically drastic changes, such as total deforestation of all tropical or boreal forests, may lead to feedbacks in atmospheric circulation and a changed climate that would not support the original vegetation.[104] As pure sensitivity studies of the atmospheric circulation, however, these global experiments do not attempt to mimic the land use changes that have actually occurred—they only indicate that such feedbacks may indeed be critical for the stability of the overall system. Regional climate simulations, on the other hand, have shown that at the continental scale important teleconnections may exist through which tropical forest clearing may cause a change in climate conditions in much less disturbed areas.[105]

Human land use change will likely continue and accelerate over large areas due to increasing demands for food and fiber, changes in forest and water management practices, and possibly large-scale projects to sequester carbon in forests or to produce biomass fuels. Predicting the future response of the Earth system to changes in land use and land cover will require projections of trends in the human contributions to these global changes, and this sort of modeling presents difficult challenges because of the multiple factors operating at local, regional, national, and global levels to influence local land use decisions.[106] The complex linkages between human activity and global change are equally important for activities other than land use. In particular, anthropogenic changes in material and energy fluxes, resulting from such activities as fossil fuel combustion and chemical fertilizer use, are expected to increase in the coming decades. Predictions of changes in the carbon and nitrogen cycles are sensitive to estimates of human activity, and predictions of the impacts of these global changes must take into account human vulnerability, adaptation, and response.

Representing human processes is also essential for understanding impacts of global change. Social, political, and economic mechanisms of adaptation and response determine vulnerabilities and mediate the impact of changes in biophysical systems. Responses to perceived or anticipated environmental changes by individuals, organizations, communities, markets, and governments may modify the behaviors that contribute to global change and so create feedbacks between the human and nonhuman systems.

To provide useful guidance to inform policy requires insights into all of these processes, which in turn requires observation and description of human contributions, impacts, and responses, as well as modeling and theoretical studies of the underlying social processes that shape them. Active research is under way to address these questions, and progress is being made (see Chapter 7). Significant examples of recent progress include studies of the multiple linked determinants and consequences of land use change, models of agricultural impacts of climate change that incorporate adaptive behavior, and models of human health stresses and agricultural impacts from potential climate-induced shifts in disease vector and pest populations.[107]

Causal models of social processes have large uncertainties and pose deep problems, which may be of a qualitatively different character than those associated with modeling nonhuman components of the Earth system. The diversity of societies, cultures, and political and institutional contexts may frustrate attempts to develop predictive or causal rules of human behavior that can be generalized globally. It also highlights the importance of global observations and comparative studies. Representation of human behavior at the micro- (individual) and macro- (collective) scales may require fundamentally different approaches to explanation, and linking between micro- and macroscales presents additional modeling challenges.[108] Moreover, predictive models directed to decision makers may alter the behavior they seek to explain and predict—indeed, such models may be used explicitly with that purpose.

While difficulties such as these may intrinsically limit the predictive power that can be ascribed to models of social processes, such modeling may still provide various forms of useful insights to inform policy deliberations or other decision making. There has been a rapid increase in attempts to integrate representations of human causes, impacts, and responses in models with explicit formal linkages to other components of the Earth system. Such integrated assessment models have offered preliminary characterizations of human-climate linkages, particularly through models of multiple linked human and climatic stresses on land cover; have provided preliminary characterization of broad classes of policy responses; and have been used to characterize and prioritize key policy-relevant uncertainties.[109]

This early progress gives ground for optimism, although serious difficulties remain. Studying human linkages with other components of the Earth system may be the most difficult challenge in modeling global change and the most important. Understanding human impacts and potential responses is a central purpose of the endeavor of global change research. Both the uncertainties in human processes and the sensitivity of other Earth system components to human perturbations are large. Indeed, early integrated assessment results suggest that the contribution of social and economic uncertainties to uncertainty in future impacts, and to preferred responses, are likely to exceed that of biophysical uncertainties.

SUMMARY

As the USGCRP is preparing to enter its second decade, the integrative phase, the strategy for the coming decade must establish techniques for coupling and integration of physical, biogeochemical, and the human dimension subsystem models in preparation for the construction of integrated prognostic Earth system models. The strategy should include four aspects, each of which will contribute to an overall objective of developing the prognostic modeling capacity essential to the needs of the USGCRP. These aspects are at different levels of organization: the first is at the component level where work, though advanced, is still required. The second level is at the subsystem level and focuses on the issues of boundary compatibility across key interfaces highlighted in this chapter. This will require modeling workshops involving intercomparisons of like subsystem models and intercomparisons involving coupling between adjacent subsystem models (which must match boundary conditions and fluxes). Issues of the adequacy of data for testing and rejection will be central. The third and fourth segments will be at the system level. The third level focuses on simple Earth system models, wherein models are compared to highlight differences in coupling techniques, interelement fluxes across key boundaries, and sensitivity studies to reveal the differences between models and the relative importance of individual system parameters. It sets the stage for the fourth level, which will be at the Earth system science level with richly developed components. Here the challenges will be significant.

This chapter focuses on level two: subsystem integration and linkage. Subsystem integration involves at least four key linkages: land-atmosphere, land-ocean, ocean-atmosphere, and atmospheric physics with atmospheric chemistry. In addition to this complexity, there is the essential component of the human dimension to global environmental change.

The Terrestrial-Atmosphere Subsystem

Immediate challenges that confront models of the terrestrial-atmosphere subsystem include exchanges of carbon and water between the atmosphere and land and the terrestrial sources and sinks of trace gases. An overarching grand challenge is to provide insight into the dynamics of a biosphere subjected to *multiple stresses*, which after all is the actual case we confront (see Chapter 2 and Box 10.6).

A central challenge is to develop coherent explanations for past changes in the total carbon fluxes and/or storage, to test hypotheses about the underlying causes of these changes, and to establish the capability for estimating future changes. It is now becoming evident that models of the terrestrial carbon cycle and of terrestrial ecosystem processes in general are going to play an overriding role in addressing many of the issues posed by global environmental change. The question of climate change is a case in point. Describing, characterizing, and eventually understanding and predicting the spatial patterns of changes in terrestrial carbon storage and associated fluxes are critical for understanding and coping with global environmental change. Understanding the carbon cycle is directly linked to understanding nutrient cycles, particularly nitrogen, and the water cycle, particularly soil moisture.

There is a similar challenge in understanding the hydrological cycle. For terrestrial systems themselves and their interaction with climate and the chemistry of the atmosphere, soil moisture is central. It is a key component in the land surface schemes in GCMs, since it is closely related to evaporation and thus to the apportioning of sensible and latent heat fluxes, and accurate prediction of soil moisture is crucial for simulation of primary production and of soil and vegetation biochemistry, including trace gas exchanges.

BOX 10.6

In the 1995 IPCC *Summary for Policy Makers: The Science of Climate Change,* the concluding section says that "there are still many uncertainties." This section observes that "[m]any factors currently limit our ability to project and detect future climate change. In particular, to reduce uncertainties further work is needed on the following priority topics:

- Estimation of future emissions and biogeochemical cycling (including sources and sinks) of greenhouse gases, aerosols, and aerosol precursors and projections of future concentrations and radiative properties.
- Representations of climatic processes in models, especially feedbacks associated with clouds, oceans, sea ice, and vegetation, in order to improve projections of rates and regional patterns of climate change.
- Systematic collection of long-term instrumental and proxy observations of climate system variables (e.g., solar output, atmospheric energy components, hydrological cycles, ocean characteristics, and ecosystem changes) for the purposes of model testing, assessment of temporal and regional variability, and for detection and attribution studies."

The IPCC further notes that "[f]uture unexpected, large and rapid climate system changes (as have occurred in the past) are, by their nature, difficult to predict. This implies that future climate changes may also involve "surprises." In particular, these arise from the non-linear nature of the climate system. When rapidly forced, non-linear systems are especially subject to unexpected behaviour. Progress can be made by investigating non-linear processes and sub-components of the climatic system."[110]

Dynamic vegetation models in which land use and land cover changes are interrelated in terms of processes and feedbacks offer an advanced approach to coupling the human driving variables with ecosystem response functions, hydrological dynamics, atmospheric conditions, and edaphic (fire-related) factors. Such models account for the role of transient states of secondary succession following disturbance. These developing models can simulate ecosystem responses with particular emphasis on vegetation dynamics on timescales from decades to centuries and provide a means of investigating responses to disturbances such as deforestation. However, a fundamental problem in assessing the results of terrestrial ecosystem models is a lack of good validation data.

Finally, since agricultural and forestry production provides the essential food, fuel, and economic resources for the world, monitoring and modeling of biospheric primary production are important to support global economic and political policy making. Fortunately, during the past decade of the USGCRP, it has become possible to investigate the magnitude and geographical distribution of these processes on a global scale by a combination of ecosystem process modeling and monitoring by remote sensing. While progress will be made (and is needed) on modeling terrestrial processes, more integrative studies are also needed wherein terrestrial systems are coupled to models of the physical atmosphere and eventually to the chemical atmosphere as well. Tying in the human component is clearly an important and needed future crucial step.

The Terrestrial-Ocean Subsystem

The cycling of water between land and atmosphere often produces a "residual" or runoff, and this water forms the basis of rivers and the recharge of aquifers. These flows are the focus of water transport models, which are tied to the coupled dynamics of the terrestrial ecosystem and the land-water cycle. The drainage basin, then, becomes the logical unit of organization; as its size is varied, the associated finite element grid varies in mesh size. Using the drainage basin as a focal unit allows a broad spectrum of fluvial systems to be considered.

Coupling of models between drainage basins and the nearshore will also be necessary to provide a complete analysis of the interaction of terrestrial and coastal zone ecosystems. Such coupling may require coastal physical oceanographic models linked to biogeochemical process simulations of regional land-coastal margin ecosystems. This issue is an important research topic in itself. A long-term goal is to model a series of material transformations along the entire continuum of fluvial systems from the points of terrestrial mobilization to delivery and processing in the coastal zone. The fluxes of constituents in various chemical and physical states would be included in such models.

The Ocean-Atmosphere Subsystem

This, with the terrestrial-atmosphere coupling, is a central aspect in the building and coupling of Earth system models. The ocean and the atmosphere have significantly different space and timescales (which themselves depend on what is being tracked), and they are often quite stiff as linked systems and therefore present major difficulties in perturbation experiments. There are also greatly differing degrees of parameterization with insufficient understanding as to their effects.

For this subsystem attention is focused on three specific areas: clouds in atmospheric models, carbon in the ocean, and the problem of linking ocean circulation models with models of atmospheric circulation.

Clouds

Handling the physics and/or parameterization of clouds in climate models remains a central difficulty. Clouds and their impact on climate remain the key uncertainty in estimating the sensitivity of the Earth's climate to increased greenhouse gases. Cloud modeling is a particularly challenging scientific problem in the climate and global change arena because it involves processes covering a very wide range of space and timescales.

Even the basic issue of the nature of the future cloud feedback is not clear. As the planet warms, it is likely that evaporation will increase, which could yield more clouds, but will these additional clouds enhance the greenhouse effect or damp it? This question remains open, and it is not clear how it will be answered. There are large differences in GCMs with respect to the scales of cloud microphysics and the treatment of these processes. To clarify the role of clouds in models, a hierarchy of models and observations needs to be used, and there should be greater emphasis on studies to isolate specific cloud processes. Finally, it would be useful to have a benchmark set of cloud and radiation diagnostics to be used to analyze feedbacks and compare models with observations.

Ocean Carbon

The ocean's critical role in the global carbon cycle and thus climate change is illustrated by its immense carbon reservoir and ability to continue to absorb and retain substantial quantities of excess CO_2 as atmospheric levels continue to rise. Modeling the ocean's carbon cycle is essential in part because data coverage is limited, both spatially and temporally. Realistic three-dimensional models can be used for interpolation and extrapolation. Furthermore, ocean models can be used to estimate the anthropogenic component of CO_2 in the ocean, which is difficult to estimate by direct measurement. Ocean models are far from perfect, however, and much work is required if reliable predictions of future oceanic CO_2 uptake are ever to become feasible.

There is a fundamental need to compare ocean carbon cycle models and thereby to clarify key physical and biogeochemical processes. Fortunately, this process has begun by comparing simulations of bomb and natural ^{14}C. The latter offers a powerful test of an ocean model's deep-ocean circulation, whereas the former is considered a reasonable analog for anthropogenic CO_2. Of particular value in this regard are the new high-precision measurements of oceanic carbon and ^{14}C that are now becoming available from samples collected during the WOCE and the JGOFS.

More generally, the WOCE and JGOFS datasets of carbon and CFCs in combination with the ocean topography from TOPEX/Poseidon and the next generation of satellite ocean color products, as well as a number of existing seasonal global-scale syntheses of nutrients, dissolved oxygen, surface carbon dioxide, and chlorophyll, present an unprecedented opportunity for evaluating models of the marine carbon cycle and extending our knowledge of its current state and potential future states. This is a central effort for the next decade. These data form the anvil on which to shape the next generation of ocean-atmosphere carbon cycle models, but as these data are consumed, meeting the challenge of model validation must not be postponed; this must be confronted.

Coupling and Initialization

Coupled ocean-atmosphere GCMs are fundamental to the study of the climate system. Models, by definition, are reduced descriptions of reality and hence incomplete and with error. Missing pieces and small errors can pose difficulties, as indicated above, when models of major subsystems such as the ocean and the atmosphere are coupled. Inconsistencies with processes or data between the submodels and/or incompleteness can lead to numerical drift when the models are coupled. The longer-term transient integrations needed in decadal to centennial global change challenges highlight these difficulties. The overriding challenge to modeling is prediction. This challenge is particularly acute when predictive capability is sought on timescales from seasonal to decadal to centennial and where one is confronted with a coupled stiff system like the ocean-atmosphere. It is a challenge that must be met in the coming decade.

The Atmospheric Physical-Chemical Subsystem

Models that incorporate atmospheric chemical processes provide the basis for much of our current understanding in such critical problem areas as acid rain, photochemical smog production in the troposphere, and depletion of the ozone layer in the stratosphere. These formidable problems require that models include chemical, dynamical, and radiative processes, which through their mutual interactions determine the circulation, thermal structure, and distribution of constituents in the atmosphere. That is, the problems require a coupling of the physics and chemistry of the atmosphere. Furthermore, the models must be applicable on a variety of spatial (regional to global) and temporal (days to decades) scales.

Further progress in modeling the interplay between the physics and chemistry of the atmosphere requires better knowledge in five key areas:

- Surface sources and sinks of trace gases, in particular exchanges of terrestrial ecosystems with the atmosphere and exchanges between the surface ocean and the atmosphere.
- Chemical models with a detailed set of reactions, in which transport is ignored, need to be developed.
- Transport models coupled to GCMs, with detailed representation of physical processes, including cloud formation and boundary layer transport, are required to simulate how advection, turbulence, and convection affect the chemical composition of the atmosphere.
- Hydrological processes and energy exchange, especially processes involving clouds, surface exchanges, and their interactions with radiation,

are crucially important research problems. Improvements are needed in models of aerosols and how they affect homogeneous chemistry and the hydrological cycle.

- Three-dimensional models of the middle atmosphere, which are used in relation with the ozone budget, need to be further developed.

The Human Linkage to the Earth System

Finally, human processes are linked to the Earth system as contributing causes of global change, as determinants of impacts, and through responses. Studying human linkages with other components of the Earth system may be the most difficult challenge in modeling global change and the most important. Understanding human impacts and potential responses is a central purpose of the endeavor of global change research, but both the uncertainties in human processes and the sensitivity of other Earth system components to human perturbations are large. Hence, representing the linkages between humans and other components of the Earth system poses a challenge in modeling the Earth system, and hence understanding them is essential to understanding the behavior of the whole system and to providing useful advice to inform policy and response.

Causal models of social processes have large uncertainties and pose deep problems, which may be of qualitatively different character than those associated with modeling nonhuman components of the Earth system. The diversity of societies, cultures, and political and institutional contexts may frustrate attempts to develop predictive or causal rules of human behavior that can be generalized globally. Moreover, predictive models directed to decision makers may alter the behavior they seek to explain and predict—indeed, such models may be used explicitly with that purpose in mind.

The challenges in modeling the Earth system, including the human component, are daunting, but the need for integrative insights, which models can produce, is ever more important. The challenges simply must be met.

NOTES

1. NASA (1986).
2. See http://www.gcrio.org/ipcc/cover.html.
3. Meadows et al. (1972) and Mesarovic and Pestel (1974). See also Legasto et al. (1980).
4. For a general account of models of this period, see Bolin et al. (1979) and Bolin (1981). See also Bolin et al. (1986).
5. For instance, see Fasham (1995) and Fasham et al. (1993).
6. This strategy has been devised mainly through the activities of the International Geosphere-Biosphere Programme (IGBP), primarily through its task force on Global Analysis, Interpretation, and Modeling (GAIM) and its core project on Global Change and Terrestrial Ecosystems (GCTE). See the subsequent cites to the Potsdam '95 and VEMAP intercomparison efforts. See also Heimann et al. (1997) and Kicklighter et al. (1997).
7. See Cramer et al. (in press) and Bondeau et al. (in press). Also see Churkina et al. (in press),

Kicklighter et al. (in press), Nemry et al. (in press), Ruimy et al. (in press), Schloss et al. (in press), and Hibbard and Sahagian (1998).

8. VEMAP Participants (1995), and Schimel et al. (1997a). Also Pan et al. (1998), Field et al. (1996).
9. Under the auspices of the World Climate Research Programme (WCRP), the Atmospheric Model Intercomparison Project (AMIP) was established in which the 10-year period 1979 to 1988 has been simulated by 30 different atmospheric models under specified conditions (see http://www.wmo.ch/); the Coupled Model Intercomparison Project (CMIP) is being organized in a similar manner; the Paleoclimate Model Intercomparison Project (PMIP) is comparing the response of 17 climate models to identical orbital forcing for 6,000 years.
10. For instance, see Dickinson and Henderson-Sellers (1988), Lean and Warrilow (1989), Shukla et al. (1990), and Henderson-Sellers et al. (1993).
11. Manabe and Stouffer (1994). See also Manabe and Stouffer (1993).
12. See Chapters 3 and 4 of this report; see also Chang and Battisti (1998) and Glantz (1996). Furthermore, although there appears to be an improvement in our ability to predict an El Niño, the post-El Niño dynamics remain very troublesome.
13. "Among the first technologies to be encountered on the frontiers of computer technology is the petaFLOPS architecture of computing. The 'FLOPS' in the curious name; 'petaFLOPS' comes from 'Floating Point Operations per Second,' and refers to the rate at which a computer can process instructions. A petaFLOPS computer theoretically can perform a million billion operations per second. That's equivalent to nearly 15 times all the networked computing capability in the US today. It would be roughly 10,000 times faster than the largest available massive parallel computer." From http://www.aminsights.com/peta.htm.
14. There is an exciting new national effort on Earth system models being advanced by Japan. See Normile (1997). See also http://www.sta.go.jp/umi/e-umi.html.
15. For instance, the work at the MIT Joint Program on the Science and Policy of Global Change (http://web.mit.edu/globalchange/www/) and at the Center for Integrated Study of the Human Dimensions of Global Change (http://hdgc.epp.cmu.edu/main.html) of the Department of Engineering and Public Policy (http://www.epp.cmu.edu/) at Carnegie Mellon University.
16. See http://www.gcrio.org/ipcc/cover.html.
17. E.g., Sellers et al. (1996) and Myneni et al. (1997). Also Henderson-Sellers (1993a, 1993b) and Henderson-Sellers and McGuffie (1995).
18. See previous cites to NPP intercomparasion efforts; see also Malmstrom et al. (1997) and McGuire et al. (1992, 1993, 1997). See also Melillo et al. (1993), Potter et al. (1993), Raich et al. (1991), and Schimel et al. (1994, 1997b, 1997c).
19. National Research Council (1990), page 30.
20. E.g., Melillo et al. (1996), Schimel et al. (1996), Schimel (1995).
21. E.g., see cites for the NPP intercomparasion efforts; see also Hibbard and Sahagian (1998).
22. See Houghton et al. (1996).
23. Schimel et al. (1996). Also Melillo et al. (1996).
24. See Section 2.1.3 in Schimel et al. (1996). See also Moore and Braswell (1994), Wigley (1993, 1997), and Wigley et al. (1996).
25. For an important and overall view of the terrestrial carbon cycle and the policy issues, see the recent article of the IGBP Terrestrial Carbon Working Group, "The terrestrial carbon cycle: Implications for the Kyoto protocol," *Science* 280:1393-1394, 1998.
26. Regarding the coupling of the carbon and climate system, see Section 6.7.2 (and Section 6.7.3 for the coupling of the chemistry of the atmosphere) in Kattenberg et al. (1996).
27. See Weyant et al. (1996).
28. See Dickinson and Henderson-Sellers (1988), Lean and Warrilow (1989), Shukla et al. (1990), Henderson-Sellers et al. (1993a, 1993b), Henderson-Sellers (1994), and Ciret and Henderson-Sellers (1997).

29. Raich and Nadelhoffer (1989), McGuire et al. (1996, 1997), Schimel et al. (1994, 1997b, 1997c).
30. E.g., Henderson-Sellers (1996a, b), Henderson-Sellers et al. (1995a, b), Henderson-Sellers and Verner (1995).
31. National Research Council (1998).
32. Ibid. See particularly Henderson-Sellers (1996a) and Vörösmarty et al. (1998a).
33. The IGBP report by Vörösmarty et al. (1997b) was particularly useful in developing this section of the chapter.
34. See Correll (1986). Also see van de Ven et al. (1991), Vörösmarty et al. (1989, 1997a, 1998b), Vörösmarty and Moore (1991), Walling and Probst (1997) and Wilkinson (1993).
35. E.g., Vannote et al. (1980), Sedell et al. (1989).
36. E.g., Billen et al. (1994), Gildea et al. (1986), and Vörösmarty et al. (1986).
37. E.g., Elwood et al. (1983) and Newbold (1992).
38. E.g., Hofmann (1991) and Ver et al. (1994).
39. E.g., Vörösmarty and Moore (1991) and Vörösmarty et al. (1989).
40. E.g., Famiglietti and Wood (1994a, 1994b).
41. Ibid.
42. http://www.ogp.noaa.gov/gcip/gcipover.html.
43. http://www.cptec.inpe.br/lba/index.html.
44. http://www.orstom.fr/pgardes/page_presentation_ang.html, L'Institut français de recherche scientifique pour le développement en coopération.
45. See National Research Council (1998); http://www.mbl.edu/html/ecosystems/lmer/lmer.html.
46. More broadly, an extraordinary set of data is found in Degens et al. (1985).
47. E.g., Mackenzie et al. (1993). See also Vörösmarty et al. (1991, 1989).
48. See Kalma and Calder (1995).
49. http://www.epm.ornl.gov/chammp/chammp.html.
50. Gates et al. (1996), Kattenberg et al. (1996).
51. See CLIVAR (1995). See also www.dkrz.de/clivar/hp.html.
52. See Hasselmann (1976).
53. E.g., Boer (1998).
54. Key discussions are found in Section 5.2.2 in Gates et al. (1996) and Sections 6.2.3 and 6.2.4 in Kattenberg et al. (1996).
55. See Section 4.2 in Dickinson et al. (1996). See also Section 8.2.3 in Santer et al. (1996).
56. Ramanathan (1995), Cess et al. (1995), Sherwood et al. (1994), Ramanathan and Collins (1991), Ramaswamy and Ramanathan (1989).
57. Kattenberg et al. (1996).
58. FANGIO Workshop (1993).
59. See J. F. B. Mitchell's working paper for the JSC/CLIVAR Working Group on Coupled Models, September 1997. See also Section 4.2.5 (particularly p. 206) in Dickinson et al. (1996) and Cess et al. (1996).
60. See (particularly Section 11.6) McBean et al. (1995). See also Section 6.7 (particularly Section 6.7.1) in Kattenberg et al. (1996).
61. See Wielicki et al. (1995).
62. There is important work in GEWEX that holds promise for the future, but more effort needs to be made on attacking this important and vexing research issue. See Chahine (1992).
63. http://www.arm.gov.
64. The overarching issue of human-induced climate change raises the key issue of detecting this change. See Santer et al. (1996).
65. E.g., Najjar et al. (1992).
66. See Sarmiento et al. (1995) and Sarmiento and Le Quéré (1996).
67. http://www.ipsl.jussieu.fr/ocmip/.

68. For an excellent overview of the modern history and the issues confronting the modeling of ocean circulation, see Semtner (1995).
69. See Section 5.3.3 in Gates et al. (1996). For a particularly provocative article, see Broecker (1997).
70. Kattenberg et al. (1996, p. 346).
71. See http://www.gcrio.org/ipcc/cover.html.
72. http://topex-www.jpl.nasa.gov/index.html.
73. http://www.soc.soton.ac.uk/OTHERS/woceipo/ipo.html.
74. http://www.igbp.kva.se/.
75. http://ads.smr.uib.no/jgofs/jgofs.htm.
76. For a good discussion of these issues, see (particularly Section 10.3.2) Denman et al. (1996).
77. Sarmiento and Le Quéré (1996).
78. E.g., Najjar et al. (1992).
79. For instance see Fasham (1995) and Fasham et al. (1993). Also, Sarmiento et al. (1993) and Hurtt and Armstrong (1996), Flynn and Fasham (1997), Popova et al. (1997), Ryabchenko et al. (1997).
80. For a slightly broader set of modeling issues, see Section 10.4 in Denman et al. (1996).
81. Until recently this "nutrient-restoring" approach was limited to annual mean models (Najjar et al., 1992) due to the lack of seasonally resolved surface nutrient observations. An intensive data archeology program at the National Oceanographic Data Center has resulted in a much larger global database of nutrients (see Levitus et al., 1993, and Levitus and Boyer, 1994), so that seasonal analyses are now possible (e.g., Anderson and Sarmiento, 1994, 1995; Sarmiento and Le Quéré, 1996; Najjar and Keeling, 1997).
82. E.g., Gruber et al. (1996).
83. The role of the biological pump in the ocean carbon cycle, discussed only briefly in Houghton et al. (1996); Sections 1.3.3.3 and 1.4.3 are expanded and updated here. From Section 10.3.2.1 in Denman et al. (1996).
84. http://ads.smr.uib.no/jgofs/jgofs.htm.
85. See again Denman et al. (1996).
86. E.g., Broecker et al. (1985, 1995).
87. http://ingrid.ldgo.columbia.edu/sources/.geosecs.
88. See OCMIP discussion on http://www.ipsl.jussieu.fr/OCMIP.
89. E.g., Lefevre et al. (1996, 1998), Takahashi and Sutherland (1995), Takahashi et al. (1997).
90. E.g., Warner and Weiss (1992), England et al. (1994), and England (1993, 1995), Dixon et al. (1996), and Warner et al. (1996). See also Rhein (1994) and Smethie and Pickart (1993).
91. http://topex-www.jpl.nasa.gov/index.html.
92. E.g., Yoder et al. (1993) and Banse and English (1994).
93. For an important discussion of the radiative forcing implications associated with the chemistry of the atmosphere, see Schimel et al. (1996).
94. For instance, see Langner and Rodhe (1991), Kanakidou and Crutzen (1993), Chuang et al. (1994), Cooke et al. (1996), Klonecki and Levy (1997), Berntsen et al. (1996, 1997), and Berntsen and Isaksen (1997).
95. For an example array of atmospheric chemistry models see http://www-pcmdi.llnl.gov/, http://www.gfdl.gov/gfdl research.html, and http://www-as.harvard.edu/chemistry/trop/index.html.
96. See Sections 2.2.1 and 2.3.2 in Schimel et al. (1996).
97. E.g., Hough (1991) and Wang et al. (1998).
98. The importance of this associated effort can be seen in Ciais et al. (1997a, 1997b) and Bousquet et al. (1996).
99. We note that this is not an exhaustive review of chemistry-climate models and that the selection of the two models from the NCAR is simply for exposition. There are advanced chemistry-climate (or circulation) models in Europe (e.g., Max Planck) and in the United States

(again for an example array of atmospheric chemistry models in the United States see http://www-pcmdi.llnl.gov/, http://www.gfdl.gov/gfdl_research.html, and http://www-as.harvard.edu/chemistry/trop/index.html.) Finally, in the context of climate modeling see also Section 6.7.3 in Kattenberg et al. (1996).

100. See http://www.esd.ornl.gov/programs/NIGEC/; see also http://cdiac.esd.ornl.gov/programs/NIGEC/fluxnet/index.html.
101. See http://www.unitus.it/eflux/euro.html.
102. See http://cdiac.esd.ornl.gov/programs/NIGEC/fluxnet/japan.txt.
103. An important summary of issues is provided by Bruce et al. (1996).
104. E.g., Claussen (1996) and Kutzbach et al. (1996).
105. E.g., Dickinson and Henderson-Sellers (1988), Salati (1986), Lean and Warrilow (1989), and Shukla et al. (1990).
106. A good introduction to this important literature can be found through the IGBP-IHNP Core Project: Land Use Cover Change (LUCC). See http://www.icc.es/lucc.
107. See again Bruce et al. (1996).
108. The important issue of scaling is addressed more fully in Gibson et al. (1998). See also http://www.uni-bonn.de/ihdp.
109. An important summary of progress on integrated assessment modeling can be found in Nakicenovic et al. (1994). See also the related publications Kaya et al. (1993) and Nakicenovic et al. (1994a, 1994b).
110. Houghton et al. (1996).

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11

Findings and Recommendations

The National Reseach Council's (NRC) Committee on Global Change Research (CGCR) is charged with providing scientific advice to the federal government on how the United States should execute global change research. The present report addresses this task and the challenge of defining a new strategy for the U.S. Global Change Research Program (USGCRP) by identifying and considering the pivotal unanswered Scientific Questions in six fields: ecosystems, seasonal to interannual climate change, decadal to centennial climate change, atmospheric chemistry, paleoclimate, and human dimensions of global change. For each field the committee discusses the character of the scientific problems; presents case studies associated with specific relevant transitions in our scientific understanding of the Earth system; defines the primary unanswered scientific questions; critically reviews lessons learned in the course of achieving scientific transitions; and extracts from the analysis a set of research imperatives that, together with the corresponding critical unanswered scientific questions address fundamental needs to know in health, public policy, economics, international relations, and national leadership.

Observational priorities flow from the identified Research Imperatives and Scientific Questions, as do the required data and information systems to manage these observations as well as some of the fundamental modeling issues that must be addressed to link the observations with the questions.

RESEARCH IMPERATIVES AND SCIENTIFIC QUESTIONS—DRIVERS OF OBSERVATIONS AND RESEARCH

The Research Imperatives, which were reviewed by the committee in significant detail, provide the foundation for the findings and recommendations regarding actions needed to shape and implement the USGCRP over the coming decade. The Research Imperatives also set the direction and the metric to measure progress within the program.

Finding 1.1: Consideration of the identified Research Imperatives, case studies, and lessons extracted from two decades of research leads to the finding that vital improvements are possible in the execution of global change research. A large number of the most important advances in understanding the Earth system and in applying the findings to key policy questions have emerged from innovative combinations of individuals, observations, and modeling that attack specific questions. For example, the El Niño-Southern Oscillation/Tropical Oceans and Global Atmosphere program laid the groundwork for operational predictions to support natural resource decisions, and the stratospheric ozone research programs set the scientific foundation for the Montreal Protocol.

Fundamental scientific progress in the future will hinge on critical decisions about the character of the scientific program and the associated essential observations. Resources have been most effectively utilized when applied in ways that strengthen the link between primary unanswered questions and the nation's intellectual resources, that improve the potential for technical innovations, that provide educational and public outreach opportunities, and that serve the vital information needs of decision makers.

Finding 1.2: Within each of the six topical themes identified in this report to further understanding of global change, the specific central scientific issues listed below must be confronted.

Finding 1.2a: Within *Changes in the Biology and Biogeochemistry of Ecosystems,* the following central scientific issues must be confronted:

- Understand the relationships between land surface processes, including land-cover change, climate, and weather prediction.
- Understand the changing global biogeochemical cycles of carbon and nitrogen.
- Understand the responses of ecosystems to multiple stresses.
- Understand the relationship between changing biological diversity and ecosystem function.

Finding 1.2b: Within *Changes in the Climate System on Seasonal to Interannual Timescales,* the following central scientific issues must be confronted:

- Maintain and improve the capability to make ENSO predictions.
- Define global seasonal to interannual variability, especially the global monsoon systems, and understand the extent to which it is predictable.

- Understand the roles of land surface energy and water exchanges and their correct representation in models for seasonal to interannual prediction.
- Improve the ability to interpret the effects of large-scale climate variability on a local scale (downscale).
- Understand the seasonal to interannual factors that influence land surface manifestations of the hydrological cycle, such as floods, droughts, and other extreme weather events.

Finding 1.2c: Within *Changes in the Climate System on Decadal to Century Timescales,* the following central scientific issues must be confronted:

- Understand patterns in the climate system.
  —*Natural Climate:* Improve knowledge of decadal to century-scale natural climate patterns, their distributions in time and space, their optimal characterization, mechanistic controls, feedbacks, and sensitivities, including their interactions with, and responses to, anthropogenic climate change.
  —*Paleorecord:* Extend the climate record back through data archeology and paleoclimate records for time series long enough to provide researchers a better database with which to analyze decadal to century-scale patterns. Specifically, achieve a better understanding of the nature and range of natural variability over these timescales.
  —*Long-Term Observational System:* Ensure the existence of a long-term observing system for a more definitive observational foundation to evaluate decadal to century-scale variability and change. Ensure that the system includes observations of key state variables as well as external forcings.
- Address the issues of those individual climate components whose resolution will most efficiently and significantly advance our understanding of decadal to century (dec-cen) climate variability.

Finding 1.2d: Within *Changes in the Chemistry of the Atmosphere*, the following central scientific issues must be confronted:

- Define and predict secular trends in the intensity of ultraviolet exposure that the Earth receives by documenting the concentrations and distributions of stratospheric ozone and the key chemical species that control its catalytic destruction and by elucidating the coupling between chemistry, dynamics, and radiation in the stratosphere and upper troposphere.
- Determine the fluxes of greenhouse gases into and out of the Earth's subsystems and the mechanisms responsible for the exchange and distribution between and within those subsystems.

- Develop the observational and computational tools and strategies that policy makers need to effectively manage ozone pollution; elucidate the processes that control and the relationships that exist among ozone precursor species, tropospheric ozone, and the oxidizing capacity of the atmosphere.
- Improve atmospheric models to better represent current atmospheric oxidants and predict the atmosphere's response to future levels of pollutants.
- Document the chemical and physical properties of atmospheric aerosols; elucidate the chemical and physical processes that determine the size, concentration, and chemical characteristics of atmospheric aerosols.
- Document the rates of chemical exchange between the atmosphere and ecosystems of critical economic and environmental import; elucidate the extent to which interactions between the atmosphere and biosphere are influenced by changing concentrations and depositions of harmful and beneficial compounds.

Finding 1.2e: Within *Paleoclimate* the following central scientific issues must be confronted:

- Document how the global climate and the Earth's environment have changed in the past and determine the factors that caused those changes. Explore how this knowledge can be applied to understand future climate and environmental change.
- Document how the activities of humans have affected the global environment and climate and determine how those effects can be differentiated from natural variability. Describe what constitutes the natural environment prior to human intervention.
- Explore the question of what the natural limits are of the global environment and determine how changes in the boundary conditions for this natural environment are manifested.
- Document the important forcing factors that are and will control climate change on societal timescales (season to century). Determine what the causes were of the rapid climate change events and rapid transitions in climate state.

Finding 1.2f: Within *Human Dimensions of Global Environmental Change*, the following central scientific issues must be confronted:

- Understand the major human causes of changes in the global environment and how they vary over time, across space, and between economic sectors and social groups.
- Determine the human consequences of global environmental change on key life-support systems, such as water, health, energy, natural ecosys-

tems, and agriculture, and determine the impacts on economic and social systems.

- Develop a scientific foundation for evaluating the potential human responses to global change, their effectiveness and cost, and the basis for deciding among the range of options.
- Understand the underlying social processes or driving forces behind the human relationship to the global environment, such as human attitudes and behavior, population dynamics, institutions, and economic and technological transformations.

Recommendation 1: Research priorities and resource allocations must be reassessed, with the objective of tying available resources directly to the major unanswered Scientific Questions identified in this report. The USGCRP's research strategy should be centered on sharply defined and effectively executed programs and should recognize the essential need for focused observations, both space-based and in situ, to test scientific hypotheses and document change.

An additional finding flows from the report and Recommendation 1.

Finding 1.3: In spite of the initial efforts to encompass a broad view of the Earth system, certain critical research areas continue to suffer either because their relationship with global change research was not clearly articulated initially or because they cross over disciplinary boundaries of environmental science. For example, the important issue of biodiversity is not adequately addressed by the USGCRP. Biodiversity research is often quite germane to global change research (and vice versa)—for example, see Finding 1.2a—and there are important interactions between global change and biodiversity loss, but biodiversity research also has major components and activities that are beyond the scope of global change research. The U.S. science community has been unable to resolve related boundary issues. Because the CGCR is recommending a sharpening of focus for the USGCRP, the issue of addressing more fully the scientific issues posed by biodiversity is more likely to be left unresolved unless there is a deliberate effort by the USGCRP agencies and the NRC to help resolve this problem. The emergence of the DIVERSITAS program demonstrates that it is beginning to be addressed better internationally.

Crosscutting Themes

Two common linked themes emerge clearly from the identified Research Imperatives, Scientific Questions, and associated observations:

- the water and carbon cycles, and
- issues of climate prediction, including the role of and impacts on human and generational (30-year) timescales and at spatial scales useful for critical public and private policy decisions.

The scientific strength of the case linking release of greenhouse gases to climate change is central to any considered action and must be commensurate with the economic impact of any proposed solution. Acceptance of the evidence by policy makers and their constituent communities is a key component of public policy negotiations. This acceptance will emerge not merely from refinement of assessment models but rather from carefully executed observations of the physical, chemical, and biological variables that track the actual state of the Earth. It is the accumulation of evidence from a body of studies, adhering to strict scientific standards and focus, that will provide a basis for decisions, not the results of a single study.

Knowledge of the global sources and sinks of carbon that are associated with changes in atmospheric concentrations of carbon dioxide, methane, and carbon monoxide is part of the foundation for understanding the physical, chemical, and biological processes that control our surroundings and for understanding the fractional impact of any industrial or agricultural input to that natural system.[a]

Similarly, water is at the heart of both the causes and the effects of climate change. It is essential to establish rates of and possible changes in precipitation, evapotranspiration, and cloud water content (both liquid and ice). Additionally, better time series measurements are needed for water runoff, river flow, and, most importantly, the quantities of water involved in various human uses. This crosscutting initiative can clearly build on the progress made by the Global Energy and Water Experiment of the World Climate Research Program and the Biospheric Aspects of the Hydrological Cycle project of the International Geosphere-Biosphere Programme.

Elucidating the climate system and possible anthropogenic changes, in addition to natural variability, is a paramount goal in these studies. A satisfactory demonstration of secular trends in the Earth's climate system, for example, requires analysis at the forefront of science and statistical analysis. Model predictions have been available for decades, but a clear demonstration of their validity, a demonstration that will convince a reasoned critic on cross examination, is not yet available. This is not in itself either a statement of failure or a significant surprise. Rather, it is a measure of the intellectual depth of the problem and the need for carefully orchestrated, long-term observations.

[a] Carbon monoxide is not a greenhouse gas, but it is involved with the chemistry of other greenhouse gases (e.g., carbon dioxide, methane).

Finding 2.1: Key crosscutting scientific themes that emerge from the total set of Research Imperatives and Scientific Questions must be addressed in an integrated fashion.

Finding 2.2:
- International negotiations will hinge on the strength of the evidence defining global-scale sources and sinks of carbon. Innovative approaches exist that can provide vital knowledge to define current carbon sources and sinks.
- Water is at the heart of climate change and the impacts of climate variability. Any assessment of climate change, its causes and impacts, must be based on significantly better observations of the water cycle.
- Observing, documenting, and understanding climate change are central responsibilities of the U.S. effort in global change research. Predictive capabilities must be developed on temporal and spatial scales particularly relevant to the coming generation of citizens. Scientific focus, continuity, and insight are critical ingredients in this pursuit. An innovative combination of observations is required on all timescales: seasonal to interannual and decadal to centennial.

Recommendation 2: Following on Recommendation 1, the national strategy of the USGCRP for Earth observations must be restructured and must be driven by the key unanswered Scientific Questions. Observational capability must be developed to support research addressing critical *common themes* within these scientific elements. Foremost among these themes are the following:
- understanding the Earth's carbon and water cycles;
- characterizing climate change, including the human dimensions component, on temporal and spatial scales relevant to human activities;
- and elucidating the links among radiation, dynamics, chemistry, and climate.

The USGCRP *must develop an approach that satisfies a number of critical objectives:*

- Improves the ability to establish accurate time series of spatially resolved flux measurements of carbon species and their isotopes and associated observations of molecular oxygen.
- Clarifies the distribution and fates of water.

- Establishes the spatial and temporal distribution of the phases of water in the middle to upper troposphere.
- Defines climate change on temporal and spatial scales relevant to current and emerging issues of public policy.
- Provides the capability to resolve sharp nonlinearities within the Earth system that are triggered by chemical composition changes, which in turn lead to phase changes that markedly affect the transport of infrared radiation.

A Coherent Observational Strategy

The Research Imperatives help identify preliminary emphases for required observations and data systems and focus the needed calculations and models; the Scientific Questions provide the specificity required to establish what must be done to advance our understanding. The required observations (whether relating to long-term trends in radiance to space, fluxes of carbon-containing molecules into and out of a particular ecosystem, chemical and isotopic composition in ice core samples, depth profiles of temperature and salinity, rate-limiting free radical concentrations as a function of nitrogen loading, or other phenomena) are outlined, where possible, with respect to accuracy, spatial and temporal resolution, required simultaneous measurements, and other defining characteristics so that each measurement ensemble is formulated to answer a specific primary Scientific Question.

The importance of accuracy, continuity, calibration, documentation, and technological innovation in observations for long-term trend analysis of global change cannot be overemphasized. A central tenet of the Committee's analysis is the necessity for the continuity of key global change observations.[b] For example, with regard to the fundamental forcing parameters of global change, such as solar radiation and atmospheric carbon dioxide concentration, and response parameters, such as surface temperature and global cloudiness, discontinuities in the climate record resulting from instrument changes or drift have led to questions about the very nature of global change. Instrument or technology changes per se are not the problem; the problem is inadequate cross-calibration between instruments, and this inadequacy usually results from the absence of commitment to observational continuity. The Research Imperatives identified in this report express guiding considerations for the USGCRP to fulfill its responsibility for observing, documenting, and understanding global environmental change.

The critical nature of high-quality observations to the scientific and public policy issues posed by global environmental change places demands and con-

[b] We note again that the importance is in the continuity of the measurement and not in the continuity of the technology or the exact instrument.

straints on whatever path a USGCRP observational strategy attempts to chart; however, a specific, well-considered, and realistic strategy, including costs and schedule, for obtaining the observations of past, present, and future expressions of global environmental change is ***essential***. The strategy will need an effective institutional mechanism for implementation. As an example, no agency currently has the responsibility for carrying out or coordinating a comprehensive program of climate observations.

There are many different scientific demands for observations for exploratory surveys, hypothesis testing in coordinated process studies, repetitive analysis-forecast cycle research, documentation of long-term changes, calibration and validation of measurements, and applications or modifications of measurements that may be used primarily for purposes other than global change research. These different demands or applications must be taken into consideration in developing a coherent observational strategy.

Operational demands are uniquely linked to long-term measurements and therefore are vital for obtaining them. In particular, the satellite and in situ measurements taken as part of the weather-observing system are critical to the future of the climate record. Development of the next generation of weather satellites (e.g., the National Polar-Orbiting Operational Environmental Satellite System, NPOESS) should be undertaken with the climate record and other research on relevant global change Scientific Questions clearly in mind.

Documentation of decadal and longer-term change raises other basic issues of program management and decision structure. Because adequate characterization of higher-frequency variability is fundamental to this documentation, both to avoid aliasing and to help in attributing causes, there is major overlap between long-term observations and measurements that are necessary on the daily and interannual timescales. However, as the timescale of the phenomenon studied becomes longer, two other considerations become increasingly important for adequate management of the research enterprise.

First, the need for comparability of measurements made at different times and places requires that high priority be given to thorough instrument calibration and measurement system validation, including the inevitable changes in technologies and observing networks. Because action is required now but all the specific Scientific Questions may not come into focus for many years, it is necessary to invoke the concept of stewardship to justify this effort. Stewardship involves doing what is reasonable and prudent to safeguard the interests of future generations, who are not able to argue their case for the data and information.

Second, to put even reliably observed interdecadal changes in context, it is necessary to invoke records of much longer duration than available based on modern instrumentation. Thus, the strategy must include the systematic search for, and recovery and exploitation of, naturally existing proxies for such instrumentation, proxies that reveal the past history over hundreds and thousands of years with adequate fidelity and temporal resolution. This activity would appear to have little relationship to what is conventionally known as an observing system. Moreover, both calibration of such proxy records in terms of modern instrumental measurements and execution of process studies aimed at their interpretation are less glamorous tasks than launching satellites to observe fine details over the next decade or so. Nevertheless, these less glamorous activities may yield much more useable information for the foreseeable future about the natural processes leading to environmental fluctuations on such timescales and hence about the modifications induced by human activities.

A coherent observational strategy is needed that builds on the identified Research Imperatives and Scientific Questions and on available national and international space and in situ networks. The USGCRP must find a mechanism to resolve the agency boundary issues that will surely arise in developing and especially in implementing a coherent observational strategy. The United States and its international partners must find a way to deal effectively with the international dimensions of an overall observational system. In sum, what is needed is not a vast new program but rather attention to coordinating, simplifying, and focusing current and planned observing systems. This work requires the sustained attention of the scientific community and the farsightedness of government to ensure the survival of key observational records. A particular challenge will be the in situ systems.

Finding 3.1: Although extensive planning has been done for space-based systems to observe global climate, the oceans, and the land, a comprehensive space-based system does not yet exist in practice. It is a promise that remains unfulfilled. Moreover, it is not clear that current planning activities will lead to such a system. Central issues about which nation (or nations) will provide which observations, for how long, and at what spatial and temporal scales (and with what assurance) remain unresolved. The situation for in situ observations across the full global environmental change agenda is in far worse shape.

Finding 3.2: The connectivity of the National Oceanic and Atmospheric Administration's (NOAA) NPOESS program with the National Aeronautics and Apace Administration's (NASA) Earth Observing System (EOS) in Mission to Planet Earth is an important and not yet adequately resolved issue. The adequacy of the NPOESS measurements to meet the demands of global change research remains in question. In addition, it is essential to maintain those stations of the existing in situ weather observation network of the United States and around the world that carry the climate record from past decades. The current and future state of this system is unclear.

Although the committee recognizes the danger in recommending another study or planning exercise, a path to a more realizable, logical, focused, and robust observing system must be found. The USGCRP must adopt multiple observational approaches, recognizing that no single approach can guarantee continuity and accuracy of measurements and that independent checks are necessary to obtain verifiable results.

Recommendation 3: The strategy for obtaining long-term observations designed to define the magnitude and character of Earth system change must be reassessed. Priority must be given to identifying and obtaining accurate data on key variables carefully selected in view of the most critical Scientific Questions and practically feasible measurement capabilities.

The strategy must take the following into account:

- The fact that observing systems have been designed for purposes other than long-term accuracy and that this has undercut the long-term calibration needed for scientific understanding of global change
- The overall balance and innovative treatment of observations: the balance between space-based observations and in situ observations, between operational and research observational systems, and between observations and analysis
- The gaps between research and operational observational systems that could threaten needed long-term records
- The end-to-end responsibility and the principal investigator mode for research observational systems.

Given the constraints on the budget system and the needs of the research community for observations from space, the strategy appears to involve three components:

- Within NASA, build focused, less costly missions on the solid and broad foundation set by EOS.
- Within NOAA, build scientifically sound observational missions for monitoring global change on the foundation set by EOS; these missions must meet NOAA's operational requirements.
- Within the USGCRP, increase the funding for in situ observational programs and the research and analysis links necessary for the related essential science.

The first component should be possible within the scope of current budget projections. The second component may require additional funds for NOAA; it may require modification of NOAA's mission (e.g., a strong commitment by NOAA to addressing global environmental change as part of its mission), and it definitely requires significantly improved coordination between NOAA and

NASA. The third component requires both new funds, which have begun to appear in the proposed fiscal year 1999 budget and sharper focus in using existing funds. With regard to the second component above, it is crucial to recognize that, even if NOAA were to assume prime responsibility for the USGCRP space-based *monitoring program*, NASA would continue to have significant data-processing responsibilities including reanalyses. Finally, the issue of the U.S. Department of Defense's role and influence on the observational space-based monitoring program must be addressed by USGCRP.

Technical Innovation

Innovation is essential for scientific progress in global change research. Many needs illuminate the importance of innovation, foresight, and testability in this field:

- Obtaining simultaneous high-resolution observations with high sensitivity of the sea surface and the marine boundary layer.
- Determining fluxes of carbon species into and out of broad categories of ecosystems.
- Establishing patterns of land use and the state of vegetation.
- Observing the vertical profiles of temperature, salinity, velocity, and tracer concentrations in the oceans.
- Establishing the distribution of water in the atmosphere and the fluxes of water between the Earth's surface and the Earth's atmosphere.
- Obtaining isotopic composition of water in the middle/upper troposphere.
- Determining systematically the concentrations and concentration derivatives of catalytically active free radicals at altitudes from the sea surface to the middle stratosphere.
- Obtaining observations along Lagrangian trajectories to dissect aerosol formation processes.

There is also a fundamental problem in global change observations that can be attacked only by technical innovation. The ocean-atmosphere-biosphere is seriously undersampled—mechanistically, spatially, and temporally.

Finding 4: The capability, availability, cost, and character of observational platforms are critical considerations in global change research strategies. Observational platforms are the foundation of the nation's research efforts, and the design of these platforms can profit significantly from the lessons learned in carrying out global change research to date. Consideration of these lessons demonstrates that the successful execution of global change research is closely tied to technical innovation. Investment in observational platforms to date has focused on a small number of large satellites, a limited number of marginally funded aircraft, a small number of ocean buoy systems, and a sparse network of ground-based efforts. This balance among the space-based, airborne, and ground-based observations does not reflect the spectrum of requirements that the Research Imperatives demand. Indeed, space-based observations and their associated data management systems dominate the resources of the USGCRP, a trend that impinges on both the research and analysis support and the in situ observational networks.

Recommendation 4: The restructured national strategy for Earth observations must more aggressively employ technical innovation. Because of fixed budgets, resources should be reallocated from the large, amalgamated space-based approach to a more agile, responsive ensemble of observations. This goal will require carefully placed investments in new technologies.

Technological advances in small satellite systems, robotics, microelectronics, and materials must be exploited to establish a sound balance between in situ ground/ocean-based, airborne, and space-based observations. Innovative treatment of the nation's research aircraft capability, piloted and robotic, is strongly advised. The research and analysis (R&A) component of the national research effort must be recognized for its central contributions to science, public policy, and understanding human dimensions issues.

Data Systems

The issue of data systems and the design of those systems are closely tied to the character of the observational strategy and the associated theoretical and modeling effort used to address the important questions. A key common component of major scientific advances has been the focus of responsibility: a specific principal investigator (or close collaboration of coinvestigators) must bear the end-to-end responsibility that connects the posing of a scientific question to the execution of an observational strategy with associated theoretical analysis through to the publication of scientific conclusions in the refereed scientific literature. A plan in which committees and/or agencies are assigned responsibility for data quality and distribution in a manner that breaks the end-to-end responsibility of the principal investigator is almost invariably critically flawed. The scientific method depends on a strategic combination of observations, selected from an array of possible observables, that can dissect a problem to the satisfaction of peer critics. This achievement demands specific choices, and it demands focused responsibility. The NRC's Committee on Data Management and Computation has already shown that effective data systems require continuous and widespread involvement of the science team.

Connected with the fundamental role of the investigator in assuring appropriateness and quality of observations is the rapidly advancing state of information systems, which can allow distribution of activities in time and space while preserving the essential responsibility of the scientific investigator. It is important, in considering the scientist and the information system, to consider the nature of the future of this interaction.

The evolution of information systems will likely be characterized by rapid, dramatic shifts, as much as by any smooth, "predictable" process. In an industry that shows a quadrupling of capability every three years, there are no stationary solutions. Stability and success can be attained only by development of a solid, well-grounded information model that describes how the pieces and subsystems, including as they develop, are related to each other. This model should be based on science that incorporates a database-driven approach; the technical implementation can then be more flexible and take advantage of technological advances in a more rational manner.

To date, the concentration has been on processing and storage, but the network infrastructure and the software are undergoing fundamental changes. Although the scientific community has logically paid attention mainly to such government and academic backbones as vBNS[c] and Internet-2, the more important shift is occurring in the widespread distribution of high bandwidths (1 to 10 Mbps) to homes. This shift has an implication for the USGCRP. First, more home users will likely be searching NASA, NOAA, and other global change archives for interesting or educational material. The networking capabilities of these more informal users will be competing with scientists for access to the archives. Second, these users will likely demand different types of products than scientists. This probable situation needs to be recognized.

The National Science Foundation's Knowledge and Distributed Intelligence solicitation in the fiscal year 1999 budget is an example of government-encouraged partnerships with the private sector that may accelerate this trend. Just as the Internet has changed the model of how we conduct research, so these new distribution channels will change the model again.

Ultimately, the USGCRP is about information. Information must flow within the program and also to the broad community of users. The subject of the program's research demands that information flow effectively to the public at large as well as to researchers. This is an important issue, and it should not be ignored by either the community of scientists engaged in global change research or the agencies that support this research with public funds.

[c] The vBNS is a nationwide network that supports high performance, high-bandwidth research applications. It was launched in 1995 and is the product of a cooperative agreement between MCI and the National Science Foundation.

Finding 5: Data systems must be agile and responsive to technology developments and to emerging techniques for data handling, analysis, and transfer. Data systems must also maintain scientific discipline and focused responsibility, so that the link between scientific question and clear scientific conclusion is not broken. An appropriate system is one that charges the government with initial-level processing and long-term archiving and the scientific community with producing the scientific products by the most effective means possible.

> **Recommendation 5:** The USGCRP must revitalize its strategy for the data systems used for global change research. Emphasis must be placed on designing and selecting flexible and innovative systems that appropriately reflect focused responsibility for data character, that provide open access to the scientific community and the public, and that rapidly evolve to exploit technological developments. In particular, the USGCRP must closely monitor the progress of the innovative "federation" concept for data systems.[d]

As suggested in the last finding, it is likely that the government will continue to provide the primary long-term archive for space and Earth science data, but it must also maintain the capability to enable long-term reprocessing of these time series; archiving must not continue to be a burial ground for data. With more rapid distribution channels and more powerful archive and processing systems at the fringes, perhaps one part of the government's role is to provide an online repository of data recipes rather than fully processed data sets. This service would enable more customized processing, with the government serving as the warehouse for raw materials and generating specific products on demand. Finally, changes in technology will allow and force us to rethink our strategy often; any strategy must accommodate and encourage this eventuality.[e]

Models and Looking into the Future

As mandated by its implementing legislation, the USGCRP seeks to provide useful information to the policy process. A direct implication of this responsibility is that the information must be scientifically credible, that it be of genuine interest and value, and that, to the greatest extent possible, it provide lead time for

[d] The "federation" concept was recommended in a 1995 National Academy of Sciences review of the USGCRP and refers to a federation of partners selected through a competitive process open to all.

[e] The committee benefited from advice from several individuals in the area of data systems and their evolution. Professor Mark Abbott was particularly constructive, and a white paper by him was most useful.

policy action. The last requirement implies provision of some prognostic information. This requirement does not necessarily entail a "prediction," but it does raise the same concerns as any prediction or predictive process. These concerns revolve around general, and not necessarily scientific, issues such as usefulness, trustworthiness, and credibility of the information. In general, a model or a set of models will often be at the center of the predictive process.

Finding 6: The policy issues that confront global change research, like the Scientific Questions, are serious, particularly with regard to their impact on humans. These issues will rely on models of exceedingly complex behaviors over a significant range of scales in space and time. Significant challenges face the scientific community in the form of many and various modeling issues, from initialization to validation. Important, unsolved, and difficult problems remain for formulating useful prognostic models over a range of topics in human dimensions research. Advances in developing *and most importantly in testing and evaluating models* are needed. **The United States is no longer in the lead in this critical field.**

The fact that the United States is no longer in the lead in applying global models is not purely a statement of criticism. Strong scientific work, particularly in the area of modeling, has been advancing around the world. This is to be applauded. Global change research, particularly in the area of prognostic activities, requires a full suite of models to adequately bracket the complex problems that the USGCRP seeks to address. Thus, advances in modeling capabilities in other parts of the world are of significant benefit to the USGCRP. Testing adequately complex models is *very* computing intensive, and if computing resources are not adequate and available, then there is clearly the danger that the dynamical aspects of models will not be sufficiently understood and hence that the models will be misapplied. Currently, the potential exists that the advanced models built in the United States cannot (or will not) be adequately tested and properly applied to key problems, such as national and regional expressions of transient climate variability and change because of a lack of available computing resources. The United States must apply greater resources, particularly (but not exclusively) in the area of advanced computing machines. National boundaries should not influence where machines are purchased.

> **Recommendation 6:** The USGCRP must foster the development and application of models at the scales of time and space needed to understand and project the specific mechanisms controlling changes in the state of the Earth system, thus providing the information required to support important policy processes. The USGCRP must give increased emphasis to models that treat multiple stresses on systems; it must therefore secure adequate computing resources so that large scale, complex models can be rigorously tested under multiple forcings.

Models must be tested and evaluated with observations. This means that adequate observations and advanced computing resources must be available to adequately evaluate models and their potential utility for the public policy process. Consequently, there must be a greater commitment to advanced computing resources, as well as human resources, by the USGCRP to ensure that global modeling is achieved at spatial and temporal scales appropriate to the needs of the policy community and the private sector.

As the USGCRP enters this second critical decade of its existence, the scientific challenges it faces are heightened by the need to understand and foreshadow the *regional* as well as other impacts of global environmental changes. The causes of global change are now also more complex, the need to understand the effects of *multiple stresses* are more apparent, and the likelihood of realizing *significant* near-term global reductions that would lead to stabilization of the forcing terms (such as greenhouse gas concentrations in the atmosphere) before a doubling of the radiative effects are more remote. In short, the need for useful prognostic information will only increase in the future. In view of these considerations, the current circumstances within the USGCRP, and the current status of modeling and available computing resources to the global change scientific community, there must be a considerably expanded commitment of resources to modeling, particularly at the temporal and spatial scales needed by the policy community.

ANNEXES

ANNEX 1

A Short History of EOSDIS, 1986 to 1995

Two revolutionary developments, one in science and one in technology, shaped early planning of EOS and its information system in the early 1980s. Both were related to rapidly increasing computational capabilities. Earth scientists developing computer models of the atmosphere and ocean realized that exchanges of energy, momentum, and mass with other parts of the Earth must be modeled and taken into account to develop an accurate simulation. They began to speak of the Earth system, realizing that the atmosphere, ocean, and biosphere were intimately connected. Simultaneously, empirical and theoretical study of the consequences of nonlinearity showed that interactions between and within the subsystems must be modeled over a wide range of spatial and temporal scales.

The same electronic components that made computers possible were being used to create sensors and spacecraft to obtain observations from space of the Earth and the heavens. The first scientific spacecraft produced new perspectives of weather systems and near-Earth space physics; those that followed returned revolutionary data about the energy balance of the Earth and about the patterns on its surface and the processes that shaped them. Together, the Earth and space sciences were building and launching satellites for making observations from and in space that produced unprecedented flows of data. The amount of data flowing from space was truly astounding in comparison with traditional sources of surface-based observations. Management of data, in addition to observing capability, became a critical issue. And scientists were beginning to realize that the key data management challenges were administrative, programmatic, and political, not technological. A recent comprehensive history of the growing tensions and their consequences in the Earth sciences demonstrates the complexities of the issues involved.[1] Here we focus more directly on the antecedents and history of the data and information system associated with the EOS.

In response to a "perception that data problems were pervasive throughout the space sciences," the Space Studies Board of the National Research Council formed the Committee on Data Management and Computation (CODMAC). In its first report this committee observed that the "majority of the current data problems are not due to technological barriers."[2] It cited problems arising from lack of scientific involvement in data system planning; inadequate funding; inadequate scientific oversight of data operations; and a long list of problems in data processing, distribution, retrieval, and archiving. After considering a number of case studies, CODMAC proposed a number of principles to guide data management, including active scientific involvement throughout data system planning and operations and a deliberate focus on users' needs. The committee also recommended that data analysis funds should be adequate and protected against reprogramming owing to delays and cost overruns.

The growing realization that human activities might be inducing global-scale change and the tremendous scientific opportunities evident in the accelerating capabilities for observation from space both stimulated new and adventuresome thinking about Earth observations in the early 1980s. In response to these new ideas, NASA appointed the Science and Mission Requirements Group for EOS and began to plan a global space-based observing system that would create a revolution in Earth science and more comprehensive understanding of the planet and its subsystems. Among its recommendations, the Requirements Group urged that observations of the Earth be continued and expanded; that a data system providing ready and integrated access to past, present, and future data be developed; and that research in understanding the data be supported.[3]

Recognizing the importance of the associated data system, the scientists and program managers involved with the fledgling EOS assembled the Data Panel to develop a rationale and recommendations for planning, implementing, and operating the EOS Data and Information System (EOSDIS). The report of the Data Panel amplified the CODMAC themes and provided a detailed examination of issues that had to be resolved for EOS and EOSDIS to be successful:[4]

- Involving scientists directly and intimately in the planning and oversight of operations of EOSDIS.
- Creating a distributed system to stimulate creativity, enable prototypes, and facilitate evolution.
- Enabling scientists to interact with a wide range of datasets that are and will be widely dispersed.
- Creating the flexibility to adapt readily to rapid advances in electronic communications, networks, and computing capabilities.
- Ensuring that archiving approaches and facilities are both responsive and reliable.

The functional system architecture developed by the EOS Data Panel envisioned that scientific users of the system would acquire data, process it, and add value to it and then return their results to the data system for use by other scientists. EOSDIS was to become an environment for stimulating scientific progress and interaction, not just a system for converting space observations transmitted to the ground as electronic bits from the instruments into datasets with variables in scientific units.

These ideas generated both optimism and further reflection in the scientific community. Some members of the community foresaw new opportunities, with EOSDIS being "responsive to the needs of science and scientists, rather than being a data archive in the form of the write-only memory . . . all too frequently encountered in the Earth sciences. [Instead], a successful EOS Data and Information System must do much more: it must be designed and implemented so that it will engender powerful new modes of research, foster synergistic interactions between observation and simulation with models, and promote thought about the Earth and its processes at higher levels of abstraction."[5] The EOSDIS, in this view, would integrate advances in workstations, local- and wide-area networks, and graphical and visualization techniques to create a new environment for scientific research. "The scientist's workstation [thus] has the potential to become a window on the world."

But establishing responsive governance of the system was critical to realizing the hopes germinated by the EOS Data Panel. EOS and EOSDIS were being created to enhance scientific understanding of the Earth and so it was argued that: "the scientific community studying the Earth must be deeply involved in the creation and management of these systems. Only the scientists at the frontiers of Earth System research can ensure that these systems remain responsive to the needs and opportunities of science."[6]

As it turned out, NASA did not take the advice of the NRC and its own advisory groups—the NASA project management structure did not permit it, and the rationale for the structure was not then questioned. Design of the EOSDIS task was made part of the EOS project. A project team at the Goddard Space Flight Center was created and tasked with the engineering design of the system. At the same time, NASA solicited proposals from the scientific community for instruments and interdisciplinary studies. Virtually all of the scientists who might have been willing to review NASA's early progress on EOSDIS were candidates to be science investigators and thus were excluded from EOS and EOSDIS activities during the competitive process. But at the end of the process, a linked group of scientific advisory committees was created, with the charter to advise (and not to decide or command) emphasized in their titles.

During this period, the design of EOSDIS had proceeded in parallel with design of the spacecraft, both efforts using the standard federal protocol for the design of hardware systems developed by the U.S. Department of Defense. For EOSDIS, formal requirements specified data flow rates, simultaneous and interactive data processing, browse and search capabilities, reprocessing demands, and archiving arrangements. Eventually, a system concept involving a highly centralized monolithic data system emerged. The community was deeply upset, the advisers protested vigorously, redesign ensued, and a system with geographically distributed components emerged that linked a number of copies of the original NASA system proposal.

The original design, so different from what the scientific community had expected, opened a crevasse between the scientific community and the NASA system designers. It was never to be satisfactorily bridged. The kind of system engineering protocol for hardware system development based on a top-down specification of requirements is antithetical to the upward flow of new capabilities envisioned to come from a logically distributed information system that stimulated creativity, using standards to link the diverse components.

Eventually, a procurement process led to award of a large contract to a private firm to complete the design and implement the system. After the first design was presented, both the NRC and NASA advisory groups advised further redesign, Congress forced EOS budget cuts, and finally an NRC group urged a return to the concept of a highly distributed system, intimately involving a range of scientists and users, that would be created and managed as a federation.[7]

This most recent NRC recommendation about EOSDIS thus echoes the Data Panel, which more than a decade ago concluded with the statement:

> There are two fundamental principles that should be followed throughout the EOS data and information system evolutionary process. They are: (i) involve the scientific community at the outset and through all subsequent activities, since the data will be acquired, transmitted, processed, and delivered for scientific research purposes; and (ii) provide the researcher with an oversight and review responsibility, since the most successful examples of data management rely on the active involvement of scientists.[8]

Unfortunately, the NASA project system could not accommodate this recommendation, but the recommendation has proved prophetic. While the Data Panel's members did not foresee explicitly the wondrous capabilities of the Internet and the World Wide Web that today can support a highly distributed EOSDIS, the panel members did understand that electronic computational and communications capabilities were rapidly creating an entirely new environment in which the vision of EOS and EOSDIS could be realized.

Some might say that the scientific community piled so many conflicting expectations on EOSDIS that it could not succeed, that the system could not be sustained with the ebb and flow of support from different parts of the community, and that it was unrealistically expensive from the very beginning. But all of these issues are independent of science or technology; they are related to governance and political sophistication. While the Data Panel and every other scientific advisory group realized that direct scientific involvement and governance were the key issues, they did not shout loudly enough, they did not provide a compelling alternative, and they did not convince those who made the decisions. Again and again, the project management juggernaut swept over their concerns and rolled onto the next redesign.

ANNEX 2

THE EOS Information Federation

The management philosophy of a federation is to make decisions at the lowest level in the organization consistent with accomplishing the task at hand.[9] This process is enabled by distributed access to information and by incentives that award achievement rather than response to central control.

Definition

An Earth Observing System (EOS) Information Federation would be an association of autonomous partners collaborating to operate an information system for the benefit of the Earth sciences and other communities. It entails a centralized structure created by the partners for leadership and administration and a decentralized management model for data processing and access to EOS data.

Purpose

The EOS Information Federation should facilitate the availability and use of information produced by, or required for, the creative activities of Mission to Planet Earth and the EOS. Thus, it should empower the global change research community to incorporate scientific, conceptual, and technical innovation and advances into the preparation and distribution of EOS products and information describing them. It should support access to, and management of, EOS information resources with in-depth expertise and capabilities, and its business practices should be based on the principle of full and open exchange of data.[10] Moreover, it should provide a flexible and effective nucleus for meeting the Earth information needs of a broad interdisciplinary community in both public and private sectors. Thus, the federation should act as a trustee of large amounts of data and information obtained at considerable expense by the U.S. and other governments for the benefit of humankind.

Basic Principles for Membership and Governance

The EOS Information Federation should be dedicated to serving the needs of a user community that includes elements of four overlapping constituencies:

- Producers of primary observational products in geophysical units, including EOS instrument teams.
- Producers, synthesizers, and consumers—including global change researchers and earth scientists using primary geophysical datasets—of higher-level scientific data products and analyses, and assimilated datasets.
- Other consumers of scientific data, including educators, students, policy analysts, and integrated assessment teams who seek reliable interpreted information.
- Producers of for-profit information, including value-added data products, for-profit data search services, and analysis, engineering, and consulting firms that use EOS data for client services.

Participation in the affairs of the federation should be open to members of these constituencies who can make significant contributions, including entities from federal or other agencies and international partners. Thus, NASA, as the principal sponsor of EOS activities, should support and foster federation policies that are open and inclusive.

The federation will need a structure that allows it to accept government and other funding, manage its activities, and be accountable to its members and the community at large. A possible mechanism would involve a board of trustees appointed by the legally responsible parents of federation members, an executive body responsible for leadership and management, and a set of councils to coordinate technical activities and resolve technical issues.

For the federation to be successful, its interests and those of its members must be similarly aligned. Members must be accountable to their sponsors and the federation. Incentives must be developed to stimulate and facilitate members to negotiate solutions to conflicts and problems. The complementary and competing interests of members must be balanced and resolved. Finally, the federation must find ways to foster and evaluate its contributions to scientific progress while recognizing that some scientists will view its efforts as competing with, rather than supporting, their own agendas.

Annex 3

Producing Trustworthy Scientific Information in the EOS Information Federation

The most significant challenge to the EOS Information Federation would be to provide trustworthy information that scientists can integrate into their research and teaching. Creating well-designed and integrated approaches to product design, production environment, and interaction with users would allow the federation and its members to address and resolve issues for the quality and trustworthiness of data and information that are long standing but rarely sufficiently resolved.

Perhaps the most important step in producing trustworthy information is managing the transition from algorithm development to maintaining a production environment. One set of issues involves scientists who develop algorithms to create information from instrument data or from other data products. If the new information is useful and in high demand, then the scientist must become the manager of a production data facility or find a way to transfer the production responsibility to others. The federation should develop a template to guide this process as it recurs within EOS and the community.

The second set of issues concerns maintaining a comprehensive perspective on product marketing. The intended purposes of a product must be thought through as part of the process of designing the product and developing an approach to distribution and delivery. Once the product is flowing to users, its success in stimulating and facilitating scientific progress must be evaluated. If a product is not being used or is not contributing to scientific advance, then its design should be reevaluated.

The following considerations will be important in creating streams of trustworthy Earth observations and derivative information:

- *Development of process monitoring tools.* To maintain active oversight without being overwhelmed by production operations, the algorithm developer must have tools to efficiently track the performance of the algorithm in the production environment. Thus, a central task is to create the theoretical and empirical envelope of expected values, for both instrument data and the results of the algorithm, so exceptions can trigger retention of diagnostic material for off-line analysis.
- *Maintaining product consistency as instruments or algorithms change.* Each change should be accompanied by a theoretical and an empirical analysis to determine whether post hoc corrections can be applied to the product within acceptable error or whether reprocessing the entire record will be necessary.
- *Documenting the process.* Inadequate documentation often prevents scientific data products from being used to their full potential, and adequate documentation is clearly essential for products monitoring long-term global change. The critical issue is whether future generations of scientists will be able to determine from archived and contemporary observations whether an apparent change is real or is an artifact of the observational and data-processing methods. Two concepts, still at embryonic stages within the Earth system science community, are likely to become a standard part of data operations.

The first is *dataset publication*—an institutionalized procedure to accomplish everything necessary to produce a high-quality, self-standing product that can be widely distributed with confidence and pride. Essential ingredients include a rigorous review of presentation and content prior to publication and a formal wrapper analogous to a book cover that uniquely identifies the product by key reference metadata, such as a title, subject, identifier, authors, and publisher. An emerging minimal standard for such metadata is the Dublin Core.[11] Adhering to this standard would at once enable library-style searches and referencing by a very broad community on the same footing as books or journal articles. A verifiable sum check and institutional signature would be added to the wrapper to provide users with an assurance of authenticity, an important attribute of trustworthy information.

The second new idea is *science concept modeling*, a process that aims to formally capture in an object-oriented metadatabase a logically complete description of the science concepts and the assumed relationships among them that were actually invoked while converting the input data into the final product, including a declarative representation of the algorithms and the decision criteria for control functions. At the highest conceptual level of such a model, abstract scientific concepts, such as four-dimensional fields of physical variables, are defined by the mathematical equations and the names that link them heuristically to the scientific literature. Beneath this descriptive layer are links to a variety of finite representations of the concepts and their associated data structures, and criteria for establishing approximate equivalence among such representations (i.e., equality within permitted tolerances). The mathematical equations are replaced by finite transformation algorithms acting on those representations and are expressed in a programming language that minimizes hidden side effects. Such a science concept model would extend the object-oriented modeling used in the ECS Data Model[12] to the metadata and scientific theory surrounding operational processing. By isolating how and where qualitative judgments were inserted by the algorithm developer or production scientist, such a model would aid the design of effective oversight procedures, which in turn could be described and recorded similarly.

- *Interactions of personnel.* The operations of the EOS Information Federation would involve delicate relationships among professional research scientists and information systems specialists. It is more likely that a variety of advantageous role models would be developed, rather than a crisp formula for success. Regardless of the size of the data-processing operation, leaders and managers must be sensitive to both the importance of addressing critical underlying issues and to the personal motivations and professional aspirations of all groups of specialists.
- *Cost benefits should accompany the effort to produce trustworthy information.*

A thoughtfully integrated processing environment leads to a higher-quality, better-documented product, with greater prospects of accurately recording the state of the Earth system and of surviving the sieve of time as a trusted source of useful long-term information. Immediate benefits come from more effective use of skilled people. Long-term benefits accrue to society through the existence of reliable information about the Earth, on which economic and policy decisions can be based. Though quality assurance appears to be costly, the alternative is the effective loss of expensive and irreplaceable data about the state of our planet.

NOTES

1. NRC (1995b).
2. NRC (1982).
3. NASA (1984).
4. NASA (1986).
5. Dutton (1989).
6. Ibid.
7. NRC (1995a).
8. NASA (1986).
9. Handy (1992).
10. NRC (1997).
11. Weibel et al. (1995).
12. Dopplick (1995).

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APPENDICES

Appendix A

PUBLIC LAW 101-606 [S. 169]; November 16, 1990 GLOBAL CHANGE RESEARCH ACT OF 1990

For Legislative History of Act, see p. 4394

An Act to require the establishment of a United States Global Change Research Program aimed at understanding and responding to global change, including the cumulative effects of human activities and natural processes on the environment, to promote discussions toward international protocols in global change research, and for other purposes.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembles,

SECTION 1. SHORT TITLE.

This Act may be cited as the "Global Change Research Act of 1990".

SECTION 2. DEFINITIONS.

As used in this Act, the term—

1. "Committee" means the Committee on Earth and Environmental Sciences established under section 102;
2. "Council" means the Federal Coordinating Council on Science, Engineering, and Technology;
3. "global change" means changes in the global environment (including alterations in climate, land productivity, oceans or other water resources,

atmospheric chemistry, and ecological systems) that may alter the capacity of the Earth to sustain life;

4. "global change research" means study, monitoring, assessment, prediction, and information management activities to describe and understand—
   A. the interactive physical, chemical, and biological processes that regulate the total Earth system;
   B. the unique environment that the Earth provides for life;
   C. changes that are occurring in the Earth system; and
   D. the manner in which such system, environment, and changes are influenced by human actions;
5. "Plan" means the National Global Change Research Plan developed under section 104, or any revision thereof; and
6. "Program" means the United States Global Change Research Program established under section 103.

TITLE 1—UNITED STATES GLOBAL CHANGE RESEARCH PROGRAM

SEC. 101. FINDINGS AND PURPOSE.

a. Findings—The Congress makes the following findings:
   1. Industrial, agricultural, and other human activities, coupled with an expanding world population, are contributing to processes of global change that may significantly alter the Earth habitat within a few human generations.
   2. Such human-induced changes, in conjunction with natural fluctuation, may lead to significant global warming and thus alter world climate patterns and increase global sea levels. Over the next century, these consequences could adversely affect world agricultural and marine production, coastal habitability, biological diversity, human health, and global economic and social well-being.
   3. The release of chlorofluorocarbons and other stratospheric ozone-depleting substances is rapidly reducing the ability of the atmosphere to screen out harmful ultraviolet radiation, which could adversely affect human health and ecological systems.
   4. Development of effective policies to abate, mitigate, and cope with global change will rely on greatly improved scientific understanding of global environmental processes and on our ability to distinguish human-induced from natural global change.
   5. New developments in interdisciplinary Earth sciences, global observing systems, and computing technology make possible significant advances in the scientific understanding and prediction of these global changes and their effects.

6. Although significant Federal global change research efforts are underway, an effective Federal research program will require efficient interagency coordination, and coordination with the research activities of State, private, and international entities.

b. PURPOSE—The purpose of this title is to provide for development and coordination of a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change.

SEC. 102. COMMITTEE ON EARTH AND ENVIRONMENTAL SCIENCES.

a. ESTABLISHMENT.—The President, through the Council, shall establish a Committee on Earth and Environmental Sciences. The Committee shall carry out Council functions under section 401 of the National Science and Technology Policy, Organizations, and Priorities Act of 1976 (42 U.S.C. 6651) relating to global change research for the purpose of increasing the overall effectiveness and productivity of Federal global change research efforts.

b. MEMBERSHIP.—The Committee shall consist of at least one representative from—
   1. the National Science Foundation;
   2. the National Aeronautics and Space Administration;
   3. the National Oceanic and Atmospheric Administration of the Department of Commerce;
   4. the Environmental Protection Agency;
   5. the Department of Energy;
   6. the Department of State;
   7. the Department of Defense;
   8. the Department of the Interior;
   9. the Department of Agriculture;
   10. the Department of Transportation;
   11. the Office of Management and Budget;
   12. the Office of Science and Technology Policy;
   13. the Council on Environmental Quality;
   14. the National Institute of Environmental Health Sciences of the National Institutes of Health; and
   15. such other agencies and departments of the United States as the President or the Chairman of the Council considers appropriate.

Such representatives shall be high ranking officials of their agency or department, wherever possible the head of the portion of that agency or department that is most relevant to the purpose of the title described in section 101(b).

c. Chairperson.—The Chairman of the Council, in consultation with the Committee, biennially shall select one of the Committee members to serve as Chairperson. The Chairperson shall be knowledgeable and experienced with regard to the administration of scientific research programs, and shall be a representative of an agency that contributes substantially, in terms of scientific research capability and budget, to the Program.

d. Support Personnel.—An Executive Secretary shall be appointed by the Chairperson of the Committee, with the approval of the Committee. The Executive Secretary shall be a permanent employee of one of the agencies or departments represented on the Committee, and shall remain in the employ of such agency or department. The Chairman of the Council shall have the authority to make personnel decisions regarding any employees detailed to the Council for purposes of working on business of the Committee pursuant to section 401 of the National Science and Technology Policy, Organization, and Priorities Act of 1976 (42 U.S.C. 6651).

e. Functions relative to global change.—The Council, through the Committee, shall be responsible for planning and coordinating the Program. In carrying out this responsibility, the Committee shall—
   1. serve as the forum for developing the Plan and for overseeing its implementation;
   2. improve cooperation among Federal agencies and departments with respect to global change research activities;
   3. provide budgetary advice as specified in section 105;
   4. work with academic, State, industry, and other groups conducting global change research, to provide for periodic public and peer review of the Program;
   5. cooperate with the Secretary of State in—
      A. providing representation at international meetings and conferences on global change research in which the United States participates; and
      B. coordinating the Federal activities of the United States with programs of other nations and with international global change research activities such as the International Geosphere-Biosphere Program;
   6. consult with actual and potential users of the results of the Program to ensure that such results are useful in developing national and international policy responses to global change; and
   7. report at least annually to the President and the Congress, through the Chairman of the Council, on Federal global change research priorities, policies, and programs.

SEC. 103. UNITED STATES GLOBAL CHANGE RESEARCH PROGRAM.

The President shall establish an interagency United States Global Change Research Program to improve understanding of global change. The Program shall be implemented by the Plan developed under section 104.

SEC. 104. NATIONAL GLOBAL CHANGE RESEARCH PROGRAM.

a. IN GENERAL.—The Chairman of the Council, through the Committee, shall develop a National Global Change Research Plan for implementation of the Program. The Plan shall contain recommendations for national global change research. The Chairman of the Council shall submit the Plan to the Congress within one year after the date of enactment of this title, and a revised Plan shall be submitted at least once every three years thereafter.

b. CONTENTS OF THE PLAN.—The Plan shall—
   1. establish, for the 10-year period beginning in the year the Plan is submitted, the goals and priorities for Federal global change research which most effectively advance scientific understanding of global change and provide usable information on which to base policy decisions relating to global change;
   2. describe specific activities, including research activities, data collection and data analysis requirements, predictive modeling, participation in international research efforts, and information management, required to achieve such goals and priorities;
   3. identify and address, as appropriate, relevant programs and activities of the Federal agencies and departments represented on the Committee that contribute to the Program;
   4. set forth the role of each Federal agency and department in implementing the Plan;
   5. consider and utilize, as appropriate, reports and studies conducted by Federal agencies and departments, the National Research Council, or other entities;
   6. make recommendations for the coordination of the global change research activities of the United States with such activities of other nations and international organizations, including—
      A. a description of the extent and nature of necessary international cooperation;
      B. the development by the Committee, in consultation when appropriate with the national Space Council, of proposals for cooperation on major capital projects;
      C. bilateral and multilateral proposals for improving worldwide access to scientific data and information; and

D. methods for improving participation in international global change research by developing nations; and

7. estimate, to the extent practicable, Federal funding for global change research activities to be conducted under the Plan.

c. RESEARCH ELEMENTS.—The Plan shall provide for, but not be limited to, the following research elements:

1. Global measurements, establishing worldwide observations necessary to understand the physical, chemical, and biological processes responsible for changes in the Earth system on all relevant spatial and time scales.
2. Documentation of global change, including the development of mechanisms for recording changes that will actually occur in the Earth system over the coming decades.
3. Studies of earlier changes in the Earth system, using evidence from the geological and fossil record.
4. Predictions, using quantitative models of the Earth system to identify and simulate global environmental processes and trends, and the regional implications of such processes and trends.
5. Focused research initiatives to understand the nature of and interaction among physical, chemical, biological, and social processes related to global change.

d. INFORMATION MANAGEMENT.—The Plan shall provide recommendations for collaboration within the Federal Government and among nations to—

1. establish, develop, and maintain information bases, including necessary management systems which will promote consistent, efficient, and compatible transfer and use of data;
2. create globally accessible formats for data collected by various international sources; and
3. combine and interpret data from various sources to produce information readily usable by policy makers attempting to formulate effective strategies for preventing, mitigating, and adapting to the effects of global change.

e. NATIONAL RESEARCH COUNCIL EVALUATION.—The Chairman of the Council shall enter into an agreement with the National Research Council under which the National Research Council shall—

1. evaluate the scientific content of the Plan; and
2. provide information and advice obtained from United States and international sources, and recommend priorities for future global change research.

f. PUBLIC PARTICIPATION.—In developing the Plan, the Committee shall consult with academic, State, industry, and environmental groups and representatives. Not later than 90 days before the Chairman of the Council submits the Plan, or any revision thereof, to the Congress, a summary of the proposed Plan shall be published in the Federal Register for a public comment period of not less than 60 days.

SEC. 105. BUDGET COORDINATION.

a. COMMITTEE GUIDANCE.—The Committee shall each year provide general guidance to each Federal agency or department participating in the Program with respect to the preparation of requests for appropriations for activities related to the Program.
b. SUBMISSION OF REPORTS WITH AGENCY APPROPRIATIONS REQUESTS.—
    1. Working in conjunction with the Committee, each Federal agency or department involved in global change research shall include with its annual request for appropriations submitted to the President under section 1108 of title 31, United States Code, a report which—
        A. identifies each element of the proposed global change research activities of the agency or department;
        B. specifies whether each element
            a) contributes directly to the Program or
            b) contributes indirectly but in important ways to the Program; and
        C. states the portion of its request for appropriations allocated to each element of the Program.
    2. Each agency or department that submits a report under paragraph (1) shall submit such report simultaneously to the Committee.
c. CONSIDERATION IN PRESIDENT'S BUDGET.—
    1. The President shall, in a timely fashion, provide the Committee with an opportunity to review and comment on the budget estimate of each agency and department involved in global change research in the context of the Plan.
    2. The President shall identify in each annual budget submitted to the Congress under section 1105 of title 31, United States Code, those items in each agency's or department's annual budget which are elements of the Program.

SEC. 106. SCIENTIFIC ASSESSMENT.

On a periodic basis (not less frequently than every 4 years), the Council, through the Committee, shall prepare and submit to the President and the Congress an assessment which—

1. integrates, evaluates, and interprets the findings of the Program and discusses the scientific uncertainties associated with such findings;
2. analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation,

human health and welfare, human social systems, and biological diversity; and
3. analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years.

SEC. 107. ANNUAL REPORT.

a. General. Each year at the time of submission to the Congress of the President's budget, the Chairman of the Council shall submit to the Congress a report on the activities conducted by the Committee pursuant to this title, including—
   1. a summary of the achievements of the Program during the period covered by the report and of priorities for future global change research;
   2. an analysis of the progress made toward achieving the goals of the Plan;
   3. expenditures required by each agency or department for carrying out its portion of the Program, including—
      A. the amounts spent during the fiscal year most recently ended;
      B. the amounts expected to be spent during the current fiscal year; and
      C. the amounts requested for the fiscal year for which the budget is being submitted.
b. Recommendations.—The report required by subsection (b) shall include recommendations by the President concerning—
   1. changes in agency or department roles needed to improve implementation of the Plan; and
   2. additional legislation which may be required to achieve the purposes of this title.

SEC. 108. RELATION TO OTHER AUTHORITIES.

a. National Climate Program Research Activities.—The President, the Chairman of the Council, and the Secretary of Commerce shall ensure that relevant research activities of the National Climate Program, established by the National Climate Program Act (15 U.S.C. 2901 et seq.) are considered in developing national global change research efforts.
b. Availability of Research Findings.—The President, the Chairman of the Council, and the heads of the agencies and departments represented on the Committee, shall ensure that the research findings of the Committee, and of certain agencies and departments, are available to—
   1. the Environmental Protection Agency for use in the formulation of a coordinated national policy on global climate change pursuant to

section 1103 of the Global Climate Protection Act of 1987 (15 U.S.C. 2901 note); and
2. all Federal agencies and departments for use in the formulation of coordinated national policies for responding to human-induced and natural processes of global change pursuant to other statutory responsibilities and obligations.

c. EFFECT ON FEDERAL RESPONSE ACTIONS.—Nothing in this title shall be construed, interpreted, or applied to preclude or delay the planning or implementation of any Federal action designed, in whole or in part, to address the threats of stratospheric ozone depletion or global climate change.

TITLE II—INTERNATIONAL COOPERATION IN GLOBAL CHANGE RESEARCH

SEC. 201. SHORT TITLE.

This title may be cited as the "International Cooperation in Global Change Research Act of 1990".

SEC. 202. FINDINGS AND PURPOSES.

a. FINDINGS.—The Congress makes the following findings:
1. Pooling of international resources and scientific capabilities will be essential to a successful international global change program.
2. While international scientific planning is already underway, there is currently no comprehensive intergovernmental mechanism for planning, coordinating, or implementing research to understand global change and to mitigate possible adverse effects.
3. An international global change research program will be important in building future consensus on methods for reducing global environmental degradation.
4. The United States, as a world leader in environmental and Earth sciences, should help provide leadership in developing and implementing an international global change research program.

b. PURPOSES.—The purposes of this title are to—
1. promote international, intergovernmental cooperation on global change research;
2. involve scientists and policymakers from developing nations in such cooperative global change research programs; and
3. promote international efforts to provide technical and other assistance to developing nations which will facilitate improvements in

their domestic standard of living while minimizing damage to the global or regional environment.

SEC. 203. INTERNATIONAL DISCUSSIONS.

a. GLOBAL CHANGE RESEARCH.—The President should direct the Secretary of State, in cooperation with the Committee, to initiate discussions with other nations leading toward international protocols and other agreements to coordinate global change research activities. Such discussions should include the following issues:
   1. Allocation of costs for global change research programs, especially with respect to major capital projects.
   2. Coordination of global change research plans with those developed by international organizations such as the International Council on Scientific Unions, the World Meteorological Organization, and the United Nations Environment Program.
   3. Establishment of global change research centers and training programs for scientists, especially those from developing nations.
   4. Development of innovative methods for management of international global change research, including—
      A. use of new or existing intergovernmental organizations for the coordination or funding of global change research; and
      B. creation of a limited foundation for global change research.
   5. The prompt establishment of international projects to—
      A. create globally accessible formats for data collected by various international sources; and
      B. combine and interpret data from various sources to produce information readily usable by policymakers attempting to formulate effective strategies for preventing, mitigating, and adapting to possible adverse effects of global change.
   6. Establishment of international offices to disseminate information useful in identifying, preventing, mitigating, or adapting to the possible effects of global change.

b. ENERGY RESEARCH.—The President should direct the Secretary of State (in cooperation with the Secretary of Energy, the Secretary of Commerce, the United States Trade Representative, and other appropriate members of the Committee) to initiate discussions with other nations leading toward an international research protocol for cooperation on the development of energy technologies which have minimally adverse effects on the environment. Such discussions should include, but not be limited to, the following issues:

1. Creation of an international cooperative program to fund research related to energy efficiency, solar and other renewable energy sources, and passively safe and diversion-resistant nuclear reactors.
2. Creation of an international cooperative program to develop low cost energy technologies which are appropriate to the environmental, economic, and social needs of developing nations.
3. Exchange of information concerning environmentally safe energy technologies and practices, including those described in paragraphs (1) and (2).

SEC. 204. GLOBAL CHANGE RESEARCH INFORMATION OFFICE.

Not more than 180 days after the date of enactment of the Act, the President shall, in consultation with the Committee and all relevant Federal agencies, establish an Office of Global Change Research Information. The purpose of the Office shall be to disseminate to foreign governments, businesses, and institutions, as well as the citizens of foreign countries, scientific research information available in the United States which would be useful in preventing, mitigating, or adapting to the effects of global change. Such information shall include, but need not be limited to, results of scientific research and development on technologies useful for—

1. reducing energy consumption through conservation and energy efficiency;
2. promoting the use of solar and renewable energy sources which reduce the amount of greenhouse gases released into the atmosphere;
3. developing replacements for chlorofluorocarbons, halons, and other ozone-depleting substances which exhibit a significantly reduced potential for depleting stratospheric ozone;
4. promoting the conservation of forest resources which help reduce the amount of carbon dioxide in the atmosphere;
5. assisting developing countries in ecological pest management practices and in the proper use of agricultural, and industrial chemicals; and
6. promoting recycling and source reduction of pollutants in order to reduce the volume of waste which must be disposed of, thus decreasing energy use and greenhouse gas emissions.

APPENDIX B

Acronyms

ABLE	Arctic Boundary Layer Expedition
AGU	American Geophysical Union
AIRI	All-India Rainfall Index
AMIP	Atmospheric Model Inter-Comparison Project
ARCSS	Arctic systems science
ARM	Atmospheric Radiation Measurement program
ARS*	USDA Agricultural Research Service
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
BAHC	Biological Aspects of the Hydrological Cycle Core Project
BASC	Board on Atmospheric Sciences and Climate
BOREAS	Boreal Ecosystem-Atmosphere Study
BSD	Board on Sustainable Development
CCM2	Community Climate Model
CCN	cloud condensation nuclei
CENR	Committee on Environment and Natural Resources
CERES	Cloud and the Earth's Radiant Energy System (NASA)
CFCs	chlorofluorocarbons
CGCR	Committee on Global Change Research
CHAMMP	Computer Hardware and Advanced Mathematics and Model Physics
CIPEC	Center for the Study of Institutions, Population, and Environmental Change

CLIMAP	Climate Mapping, Analysis, and Prediction Group
CLIVAR	Program for Climate Variability and Predictability
CMIP	Coupled Model Intercomparison Project
COADS	Comprehensive Ocean-Atmosphere Data Set
CODMAC	Committee on Data Management and Computation
COFUR	costs of filling user requests
COHMAP	Cooperative Holocene Mapping Project
COWL	cold oceans and warm land
CRREL*	DOD Cold Regions Research and Engineering Laboratory
CSREES*	USDA Cooperative State Research, Education, and Extension Service
CTD	conductivity-temperature-depth
CZCS	coastal zone color scanner
DAAC	Data Acquisition and Archive Center
DIC	dissolved inorganic carbon
DIVERSITAS	IUBS-SCOPE-UNESCO Programme on Biodiversity
DMS	dimethyl sulfide
DMSP	Defense Meteorological Satellite Program
DOC	dissolved organic carbon
DOD*	U.S. Department of Defense
DOE*	U.S. Department of Energy
DOI*	U.S. Department of the Interior
ECMWF	European Centre for Medium-Range Weather Forecasting
ENSO	El Niño-Southern Oscillation
EOS	Earth Observing System
EOSDIS	EOS Data and Information System
EPA*	U.S. Environmental Protection Agency
ERS*	USDA Economic Research Service
ESA	European Space Agency
ES*	NASA Earth Science
ESSC	Earth System Sciences Committee
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
EVE	Equilibrium Vegetation Ecology model
FANGIO	Feedback Analysis of GCMs and in Observations
FIFE	First ISLSCP Field Experiment
FS*	USDA Forest Service
FUNCEME	Fundação Cearense de Meteorologia e Recursos Hídricos (Ceará's Foundation for Meteorology and Hydrological Resources)
GAIM	Global Analysis, Interpretation, and Modelling Program
GCIP	Global Energy Water-Cycle Experiment Continental-Scale International Project

GCM	general circulation model
GCOS	Global Climate Observing System
GCTE	Global Change and Terrestrial Ecosystems Core Project
GEOSECS	Geochemical Ocean Sections Study
GEWEX	Global Energy and Water Cycle Experiment
GFDL	Geophysical Fluid Dynamics Laboratory
GIS	geographic information system
GISP2	Greenland Ice Sheet Project Two
GLOBEC	Global Ocean Ecosystem Dynamics
GLOCHANT	Global Changes in the Antarctic
GLOSS	Global Sea Level Observing System
GOALS	Global Ocean-Atmosphere-Land Surface program
GRIP	Greenland Ice Core Project
GTS	Global Telecommunication System
HALOE	Halogen Occultation Experiment
HAPEX	Hydrological and Atmospheric Pilot Experiment
HCDN	Hydroclimatic Data Network
HCN	Historical Climate Network
HSCT	High-Speed Civil Transport
HHS*	U.S. Department of Health and Human Services
ICSU	International Council of Scientific Unions
IGAC	International Global Atmospheric Chemistry program
IGBP	International Geosphere-Biosphere Programme
IHDP	International Human Dimensions Programme
IMAGES	Intermediate Model for Global and Annual Evolution of Species
IPCC	Intergovernmental Panel on Climate Change
IR	infrared
IRI	International Research Institute for Climate Prediction
ISLSCP	International Satellite Land Surface Climatology Project
ITCZ	Intertropical Convergence Zone
IUBS	International Union of Biological Sciences
JGOFS	Joint Global Ocean Flux Study
LANDSAT	Land Remote Sensing Satellite
LBA	Large-Scale Biosphere-Atmosphere Experiment
LIA	Little Ice Age
LIDAR	light detection and ranging instrument
LMER	Land Margin Ecosystem Research
LOICZ	Land-Ocean Interactions in the Coastal Zone
LSP	land surface parameterization
LTER	Long-Term Ecological Research program
LUCC	land use cover change
MBL	marine boundary layer

METOP	meteorological operational
MetOp	Meteorological Operational (Satellite)
MINK	Missouri-Illinois-Nebraska-Kansas
MISR	Multi-Angle Imaging Spectroradiometer
MLS	microwave limb sounder
MODIS	Moderate-Resolution Imaging Spectroradiometer
MTM-SVD	Multi-Taper Method/Singular Value Decomposition
MWP	Medieval Warm Period
NADP/NTN	National Acid Deposition Program/National Trends Network
NADW	North Atlantic deep water
NAFTA	North American Free Trade Agreement
NAO	North Atlantic Oscillation
NAS	National Academy of Sciences
NASA*	National Aeronautics and Space Administration
NASM*	SI National Air and Space Museum
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEP	National Center for Environmental Prediction
NDSC	Network for Detection of Stratospheric Change
NEE	net ecosystem exchange
NICHD	National Institute of Child Health and Human Development
NIEHS*	National Institute of Environmental Health Sciences
NIST*	National Institute of Science and Technology
NMNH*	SI National Museum of Natural History
NOAA*	National Oceanic and Atmospheric Administration
NPO	North Pacific Oscillation
NPOESS	National Polar-Orbiting Operational Environmental Satellite System
NPP	net primary productivity
NRC	National Research Council
NRCS*	USDA Natural Resources Conservation Service
NSF*	National Science Foundation
NSTC	National Science and Technology Council
NWS	National Weather Service
NZP*	SI National Zoological Park
OBER*	DOE Office of Biological and Environmental Research
OCMIP	Ocean Carbon Model Intercomparison Project
OCS	carbonyl sulfide
OMB	Office of Management and Budget
ONR*	DOD Office of Naval Research
ORD*	EPA Office of Research and Development
OSTP	Office of Science and Technology Policy
OSSE	Observing System Simulation Experiments

OTTER	Oregon Transect Ecological Research
PAGES	past global changes
PAN	peroxyacetylnitrate
PAR	photosynthetically active radiation
PBL	planetary boundary layer
PCI	Polar Circulation Index
PILPS	Project for Intercomparison of Land Surface Parameterization Schemes
PMIP	Paleoclimate Model Intercomparison Project
PNA	Pacific-North American
R&A	research and analysis
REA	representative elementary area
SAFARI	South African Fire-Atmosphere Research Initiative
SAGE	Stratospheric Aerosol and Gas Experiment
SAO*	SI Smithsonian Astrophysical Observatory
SCAR	Scientific Committee on Antarctic Research
SCOPE	Scientific Committee on Problems of the Environment
SEDAC	Social and Economic Data and Applications Center
SERC*	SI Smithsonian Environmental Research Center
SI*	Smithsonian Institution
SLP	sea level pressure
SOI	Southern Oscillation Index
SPADE	Stratospheric Photochemistry, Aerosol, and Dynamics Expedition
SPECMAP	Spectral Mapping Project
SPOT	Systeme Probatoire pour l'Observatión de la Terre
SST	sea surface temperature
START	Global Change System for Analysis, Research, and Training
STE	stratosphere troposphere exchange
STRI*	SI Smithsonian Tropical Research Institute
STN	Simulated Topographical Network
SURFRAD	surface radiation observations
TAO	tropical atmosphere-ocean
TIROS	Television and Infared Observation Satellite
TM	thematic mapper
TOGA	Tropical Oceans and Global Atmosphere program
TOMS	total ozone mapping spectrometer
TOPEX	Ocean Topography Experiment
TRACE-A	Transport and Chemistry near the Equator over the Atlantic
TRMM	Tropical Rainfall Measuring Mission
UARS	Upper-Atmosphere Research Satellite
UNEP	United Nations Environment Programme

UNESCO	United Nations Educational, Scientific, and Cultural Organization
USAID	U.S. Agency for International Development
USDA*	U.S. Department of Agriculture
USGCRP	U.S. Global Change Research Program
USGS*	U.S. Geological Survey
USHCN	U.S. Historical Climate Network
VEMAP	Vegetation and Ecosystem Modeling and Analysis Project
VOCs	volatile organic compounds
WCRP	World Climate Research Programme
WFS	World Fertility Survey
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment

* Agencies and Departments with research funds focused on the USGCRP.

APPENDIX C

Biographical Sketches of Committee Members

Berrien Moore III is director of the Institute for the Study of Earth, Oceans, and Space at the University of New Hampshire. He has served as chair of the National Aeronautics and Space Administration's (NASA) Space Science and Applications Advisory Committee, for which he received the Distinguished Public Service Medal. He also serves as chair of the Scientific Committee of the International Geosphere-Biosphere Programme and its Task Force on Global Analysis, Interpretation, and Modeling. Other boards on which he has been a member include the NASA Advisory Council's Committee on Earth System Science, the National Academy of Sciences' Board on Global Change, the Space Science Board's Committee on Earth Science, and the Science Executive Committee for the Earth Observing System. From 1996 until June 1998 he served as chair of the International Space Programs of the Space Studies Board. Professor Moore's computer modeling of the global carbon cycle has received worldwide attention through his publications on the contribution of terrestrial biota to the concentration of atmospheric carbon dioxide and the role of the ocean as a sink for carbon dioxide. He received his Ph.D. in mathematics from the University of Virginia in 1969.

James G. Anderson has been Harvard University's Philip S. Weld Professor of Atmospheric Chemistry since 1982. He has pioneered the in situ detection of stratospheric free radicals from balloon and high-altitude aircraft platforms. Through his research Dr. Anderson has quantitatively demonstrated the mechanisms caused by chlorofluorocarbons and other man-made chlorine compounds responsible for the observed massive springtime ozone depletion. Dr. Anderson has been a member of the National Academy of Sciences since 1992 and has received a number of honors, including the E.O. Lawrence Award in Environmental Science and Technology, the Gustavus John Esselen Award for Chemistry in the Public Interest, the United Nations Earth Day International Award, and the Ledley Prize for Most Valuable Contribution to Science by a Member of the Faculty, Harvard University. He is a member of numerous professional societies and scientific boards. Dr. Anderson holds a Ph.D. in physics/astrogeophysics from the University of Colorado.

Gregory H. Canavan is currently the senior scientific advisor for defense programs at the Los Alamos National Laboratory, where he works on remote sensing from small satellites for defense and civil applications. Previously, he has served as assistant physics division leader at Los Alamos, in the Physics Division for Advanced Concepts, as Director of the Department of Energy's Office of Inertial Fusion, and as a White House fellow. He has performed studies of strategic defense, limited defenses, and advanced conventional defenses for the White House Science Council and has served on the Offense-Defense Working Group of the Presidential Commission of "Discriminate Deterrence," on the Steering Group of the U.S. Department of Defense Midcourse Sensor Study, and as deputy chief to the Staff Group to the Chief of Staff for the U.S. Air Force, from which he retired as a colonel in 1979. Dr. Canavan was a charter member of the Defense Technology Panel of the White House Science Council and the Directed Energy Panel of the Strategic Defense Advisory Committee and is a member of the American Physical Society and the American Association for the Advancement of Science. He holds a B.S. in mathematics from the U.S. Air Force Academy, an M.B.A. from Auburn University, and an M.S. and a Ph.D. in applied science from the University of California, Davis-Livermore.

Robert Costanza is a professor at the Center for Environmental Science and the Biology Department at the University of Maryland and director of the University of Maryland's Institute for Ecological Economics. His research focuses on ecological-economic modeling on local, regional, and global scales. The president and cofounder of the International Society for Ecological Economics, Dr. Costanza serves as chief editor of its membership journal, *Ecological Economics.* He was a Pew scholar from 1993 to 1996 and has received the Distinguished Achievement Award from the Society for Conservation Biology, a Kellogg National Fellowship, the National Wildlife Federation Outstanding Publication Award, and the German Marshall Fund travel award. Dr. Costanza holds an M.A. in architecture and urban and regional planning and a Ph.D. in systems ecology, environmental engineering sciences, from the University of Florida.

W. Lawrence Gates is director of the Program for Climate Model Diagnosis and Intercomparison at the Lawrence Livermore National Laboratory in California and is currently serving as the chairman of the Joint Scientific Committee for the World Climate Research Programme. Prior to joining the LLNL, he was chairman of the Department of Atmospheric Sciences at Oregon State University. A member of the American Meteorological Society, the American Geophysical Union, and the Royal Meteorological Society, Dr. Gates conducts research in dynamic meteorology, climate dynamics, numerical weather prediction, and physical oceanography. He holds S.B., S.M., and Sc.D. degrees from the Massachusetts Institute of Technology.

Priscilla C. Grew is the vice chancellor for research at the University of Nebraska-Lincoln, where she is also a professor in the Department of Geology and the Conservation and Survey Division of the Institute for Agriculture and Natural Resources. She has served as director of the Minnesota Geological Survey, commissioner of the California Public Utilities Commission, and director of the California Department of Conservation. Dr. Grew is a fellow of the Geological Society of America, the Mineralogical Society of America, and the American Association for the Advancement of Science. She served as chair of the Geology and Geography Section of AAAS. A former member of the National Science Foundation Advisory Committee on Geosciences and the NSF Science and Technology Center's Advisory Committee, Dr. Grew holds a B.A. in geology from Bryn Mawr College and a Ph.D. in geology from the University of California at Berkeley.

Margaret S. Leinen is dean of the Graduate School of Oceanography and of the College of the Environment and Life Sciences at the University of Rhode Island. She also serves as vice provost for marine and environmental programs. Her research focuses on geochemistry, mineralogy, and sedimentology of deep-sea sediments and on paleoclimatology and atmospheric circulation in the past. Dr. Lienen is a fellow of the Geological Society of America. She holds a Ph.D. in oceanography from the University of Rhode Island.

Paul A. Mayewski is director of the Climate Change Research Center of the Institute for the Study of Earth, Oceans, and Space, and a professor of glaciology in the Department of Earth Sciences at the University of New Hampshire. He currently serves as chair of the Executive Committee for the Greenland Ice Sheet Project, as chair of the Executive Committee for the International Transantarctic Scientific Expedition, as co-chair for the Himalayan Paleoclimate Program and as director of the National Ice Core Laboratory Science Management Office. Dr. Mayewski is a fellow of the American Geophysical Union and a fellow and citation winner in the Explorers Club and has led more than 30 scientific expeditions to the Antarctic, Arctic, and Himalayas/Tibetan Plateau. He received his Ph.D. in 1973 from the Institute of Polar Studies, Ohio State University.

James J. McCarthy is a professor of biological oceanography in the Department of Organismic and Evolutionary Biology and the Department of Earth and Planetary Sciences at Harvard University. He also serves as the director of Harvard's Museum of Comparative Zoology, head tutor for degrees in environmental science and public policy, and master of Pforzheimer House. His research interests relate to the regulation of plankton productivity in the sea and in recent years have focused in particular on the cycling of nitrogen in planktonic ecosystems in diverse ocean regions. From 1986 to 1993 Dr. McCarthy chaired the international committee that establishes research priorities and oversees implementation of the International Geosphere-Biosphere Programme. He is the founding editor of the American Geophysical Union's journal *Global Biogeochemical Cycles*, a fellow of the American Association for the Advancement of Science and the American Academy of Arts and Sciences, and a foreign member of the Royal Swedish Academy of Sciences. Dr. McCarthy received his Ph.D. in oceanography from Scripps Institution of Oceanography.

S. Ichtiaque Rasool, a senior research scientist at the Jet Propulsion Laboratory in Pasadena, California, is currently a visiting research professor at the Complex Systems Research Center of the University of New Hampshire. Until recently he was director of the International Geosphere-Biosphere Program, Data and Information System, in Paris. Dr. Rasool is also cofounder and from 1981 to 1992 was chairman of the International Satellite Land Surface Climatology Project. His main research interest is the field of physics of atmospheres and remote sensing of Earth and planets. He has served as editor of the *Journal of Atmospheric Sciences* and now serves as coeditor of *Space Science Reviews* and as founding editor of the *Journal of Global Atmosphere and Ocean Systems*. The 1974 recipient of the National Aeronautics and Space Administration's medal for Exceptional Scientific Achievement and a member of the International Academy of Astronautics, Dr. Rasool received his Ph.D. in atmospheric sciences from the University of Paris.

Edward S. Sarachik is currently professor of atmospheric sciences and adjunct professor in the School of Oceanography of the University of Washington, Seattle. Previously, he held research positions with Stanford University, the National Aeronautics and Space Administration, the Massachusetts Institute of Technology, Harvard University, and the National Oceanic and Atmospheric Administration. Dr. Sarachik's research interests involve the role of the oceans in climate, climate predictability, and the applications of climate predictions for the benefit of society. In addition to his involvement in the Committee on Global Change Research, he serves on the CLIVAR Scientific Steering Group of the World Climate Research Programme and is chair of the Working Group on Forecast Applications for the International Research Institute for Climate Prediction. A fellow of the American Meteorological Society and the American Geophysical

Union, Dr. Sarachik received his Ph.D. in theoretical physics from Brandeis University in 1966.

David S. Schimel is a senior scientist in the Climate and Global Dynamics Division of the National Center for Atmospheric Research and also holds a position as senior research scientist in the College of Natural Resources, Colorado State University. He was a National Research Council senior fellow at the Ames Research Center from 1988 to 1989. His current research focuses on ecosystem effects, the carbon cycle, and isotopic analyses. Dr. Schimel received his Ph.D. from Colorado State University in 1982.

W. James Shuttleworth joined the Department of Hydrology and Water Resources of the University of Arizona in 1993, having previously been head of the Hydrological Processes Division of the Institute of Hydrology, United Kingdom. His major research interests are in physical processes in hydrology, with emphasis on evaporation and hydrometeorology, as applied to environment change at local, regional, and global scales, including the effects on global climate of Amazonian deforestation and African desertification. He serves on committees for the International Council of Scientific Unions, the International Hydrology Programme, the International Geosphere-Biosphere Programme, and the World Climate Research Programme, and is a fellow of the American Geophysical Union, the American Meteorological Society and the Royal Meteorological Society. Dr. Shuttleworth holds a Ph.D. in high-energy nuclear physics and a D.Sc. from Manchester University in the United Kingdom.

Karl K. Turekian is the Benjamin Silliman Professor of Geology and Geophysics at Yale University. His research utilizes radioactive and radiogenic isotope measurements in studying oceanic, earth surface, and atmospheric processes. He is a member of the National Academy of Sciences and a fellow of the American Academy of Arts and Sciences. He is also a fellow of several scientific societies, including the Geological Society of America, the American Geophysical Union, the Meteorological Society, and the American Association for the Advancement of Science. Dr. Turekian has served on numerous National Research Council committees and boards. He was a Guggenheim fellow at Cambridge University and a Sherman Fairchild Distinguished Scholar at Caltech. He was awarded the V.M. Goldschmidt Medal of the Geochemical Society in 1989, the Maurice Ewing Medal of the American Geophysical Union in 1997, and the Wollaston Medal of the Geological Society of London in 1998. Dr. Turekian holds an A.B. degree from Wheaton College in Illinois and a Ph.D. from Columbia University.

Peter M. Vitousek is a professor of population biology at Stanford University. A member of the Ecological Society of America, the American Association for the Advancement of Science, and the Soil Science Society of America, Dr. Vitousek conducts research on the regulation of nutrient cycling in terrestrial ecosystems and land-water interactions. He has carried out extensive experimental and comparative studies of nutrient cycling in tropical and temperate forests and has demonstrated that biological invasions by exotic species can alter ecosystem-level properties in the areas they invade. His laboratory is at the forefront of efforts to understand nutrient cycling in forest ecosystems and is now working toward understanding interactions between components of global change and terrestrial ecosystems. Dr. Vitousek holds a Ph.D. in biological sciences from Dartmouth College.

Staff Member Information

Sherburne B. Abbott joined the Policy Division of the National Research Council (NRC) in January 1997 as the executive director of the Board on Sustainable Development. She has worked with the NRC for 12 years, serving previously as the director of the Committee on International Organizations and Programs of the Office of International Affairs, and the Polar Research Board of the Commission on Geosciences, Environment, and Resources. Prior to her work with the NRC, she was assistant scientific program director for the U.S. Marine Mammal Commission, a science teacher in a private high school, and a research assistant at the Tufts University Cancer Research Center. She has published papers on environmental monitoring in Antarctica, salmonid biology, and polar research. She holds an A.B. in biology from Goucher College and an M.F.S. in ecology and natural resource policy from Yale University.

Sylvia A. Edgerton joined the Policy Division as a senior research fellow from April 1998 to April 1999 on loan from the U.S. Department of Energy through the Pacific Northwest National Laboratory. She previously served as deputy director of the coordinating Office of the U.S. Global Change Research Program and as a senior research associate for the Committee on Earth and Environmental Sciences under the Federal Coordinating Council for Science, Engineering, and Technology. She has also worked both nationally and internationally in air quality research and environmental risk assessment. Dr. Edgerton received her B.S. in physics from the University of Arizona and her M.S. and Ph.D. in environmental science from the Oregon Graduate Institute of Science and Technology.

Laura J. Sigman joined the National Research Council as a research associate with the Board on Sustainable Development and the Committee on Global Change Research in February 1997. She holds an A.B. in environmental studies from Dartmouth College.

Index

A

B

C

D

E

H

I

J

K

L

N

O

P

R

S

U

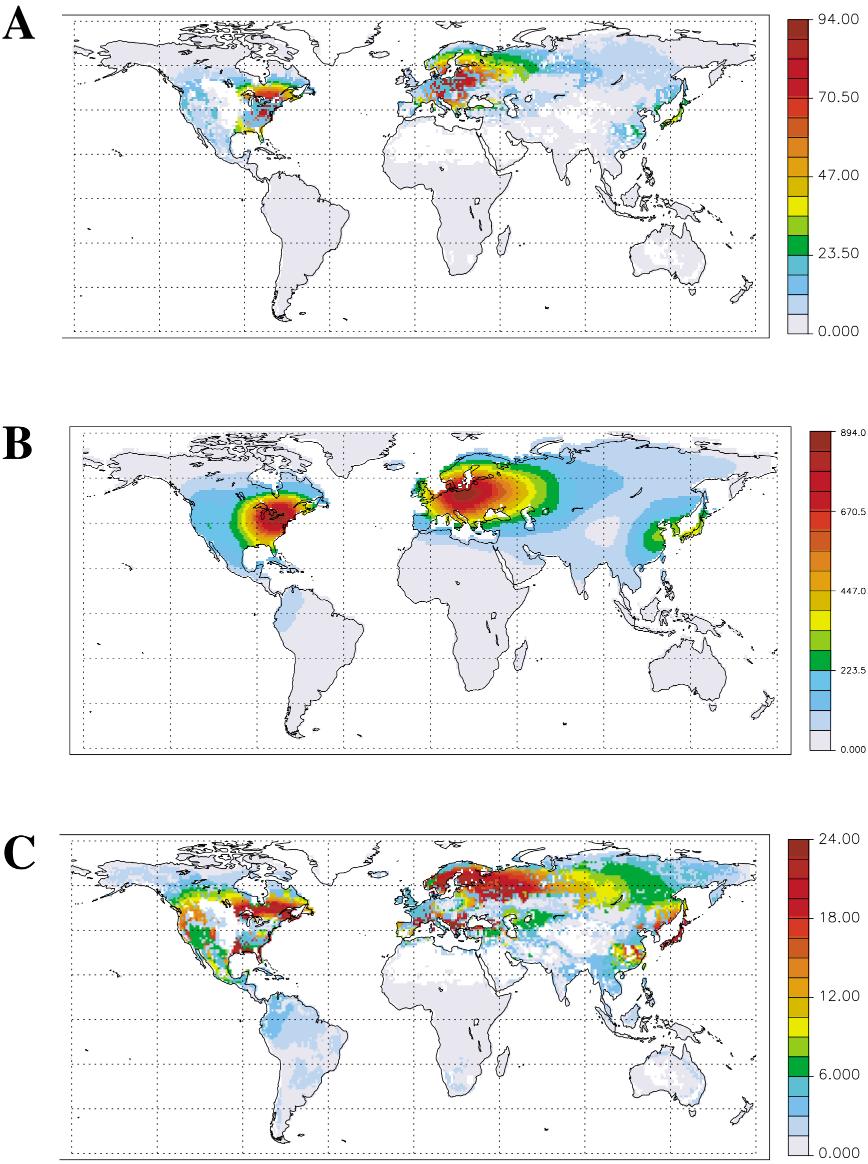
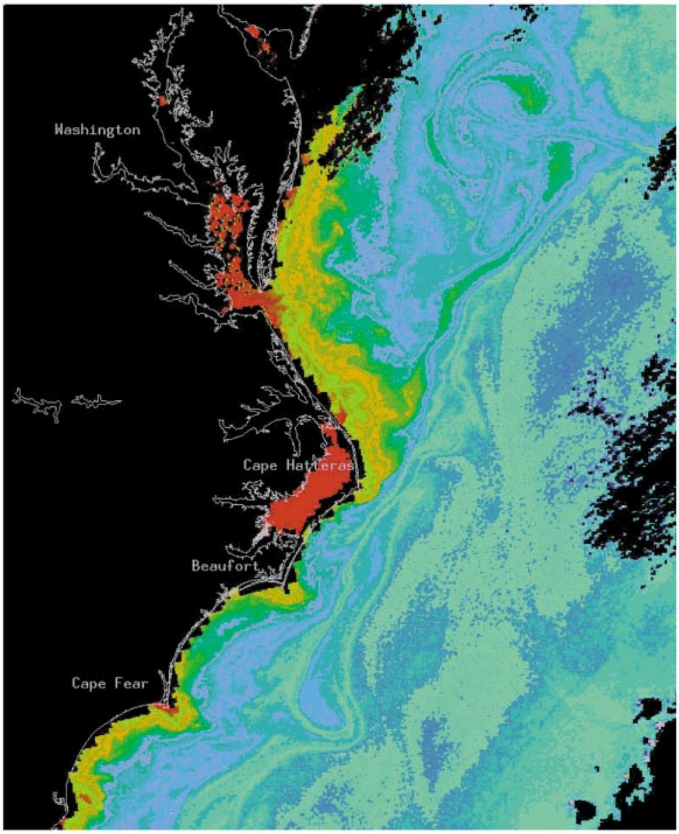


PLATE 1 (a) Spatial distribution of the 1990 carbon sink resulting from fossil fuel nitrogen deposition between 1845 and 1990. Values are in g C/m^2; the simulation used $f_w = 0.5$ and $N_{loss} = 0.2$, where total global carbon uptake was 0.74 Pg. (b) Fossil fuel nitrogen deposition on land (kg/km^2) for 1990 as estimated by the GRANTOUR atmospheric transport model (Penner et al., 1991). (c) Same as (a) except that for this simulation N_{loss} increases with N deposition. SOURCE: Townsend et al. (1996). Courtesy of the Ecological Society of America.



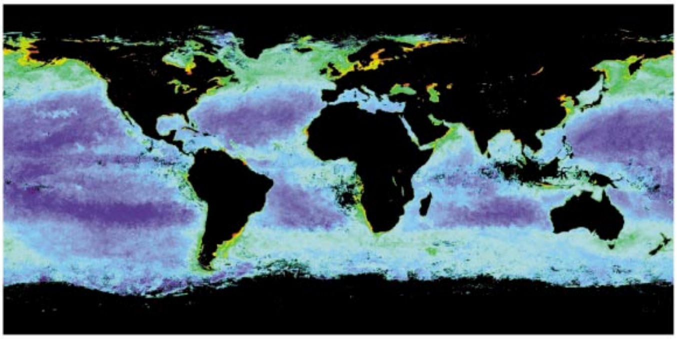


PLATE 2 New images of ocean color from the SeaWIFs instrument. The upper panel shows a high resolution of the coastal oceans off northeastern North America. The lower panel shows a global view. Ocean "color" measures the density of photosynthetic pigments in marine organisms (phytoplankton). This information, the first of its type for over 10 years, can be used to understand marine ecology, fisheries, and physical processes. SOURCE: Data from the SeaWIFs project home page (http://seawifs.gsfc.nasa.gov/SEAWIFS.html).

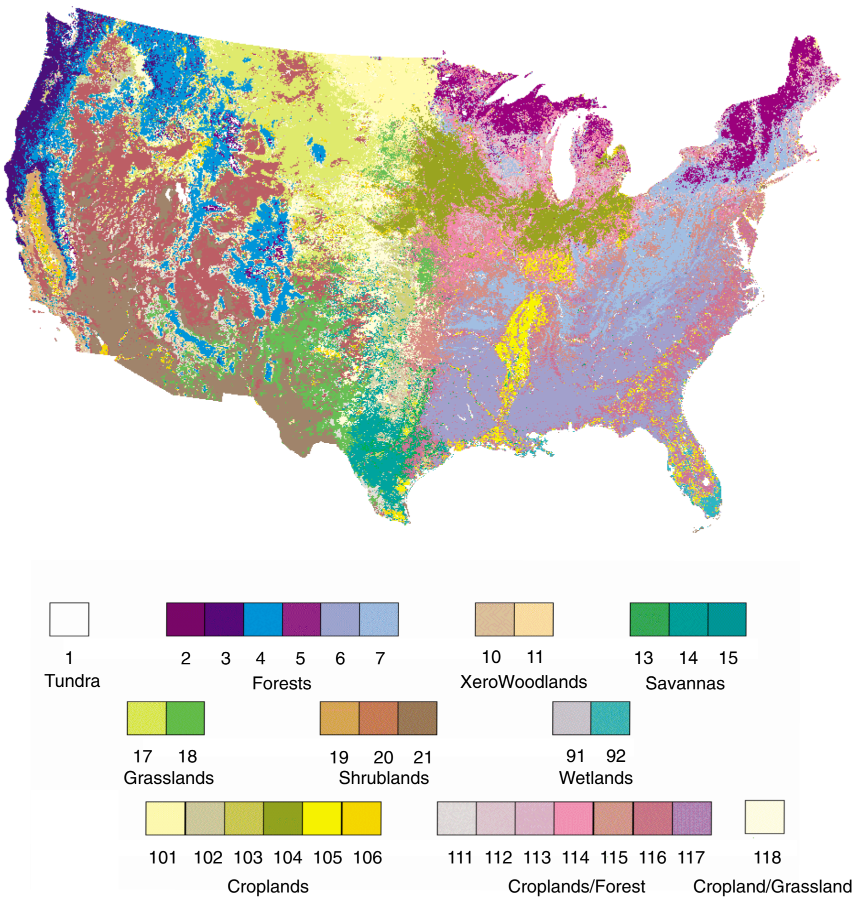


PLATE 3 Current land cover for the conterminous United States (1-km resolution). Classes under 100 are natural vegetation types (with little or some level of human management) and correspond to classes used in VEMAP (VEMAP Participants 1995; Kittel et al., 1995). Those over 100 are cover types dominated by agriculture. SOURCE: Based on Loveland et al. (1991). Courtesy of the American Society for Photogrammetry and Remote Sensing.

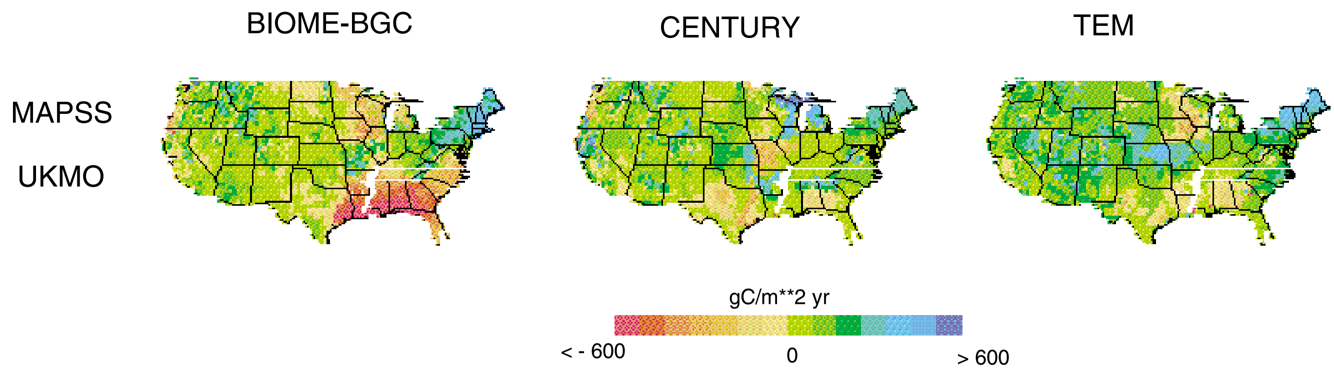


PLATE 4 Change in net primary productivity when biogeochemical models (BIOME-BGC, CENTURY, and TEM) are run using climate change scenarios from the Geophysical Fluid Dynamics Lab, United Kingdom Meteorological Office (UKMO), and OSU models and the altered vegetation distributions predicted by the biogeographic models (see Table 2.2). Results are shown for the simulations using the MAPSS biogeography model and UKMO climate. This shows patterns of change when climate change effects on ecosystem function (plant growth, respiration, nutrient cycling) and ecosystem structure (distributions of forests, grasslands, etc.) are considered together. SOURCE: VEMAP Participants (1995). Courtesy of the American Geophysical Union.

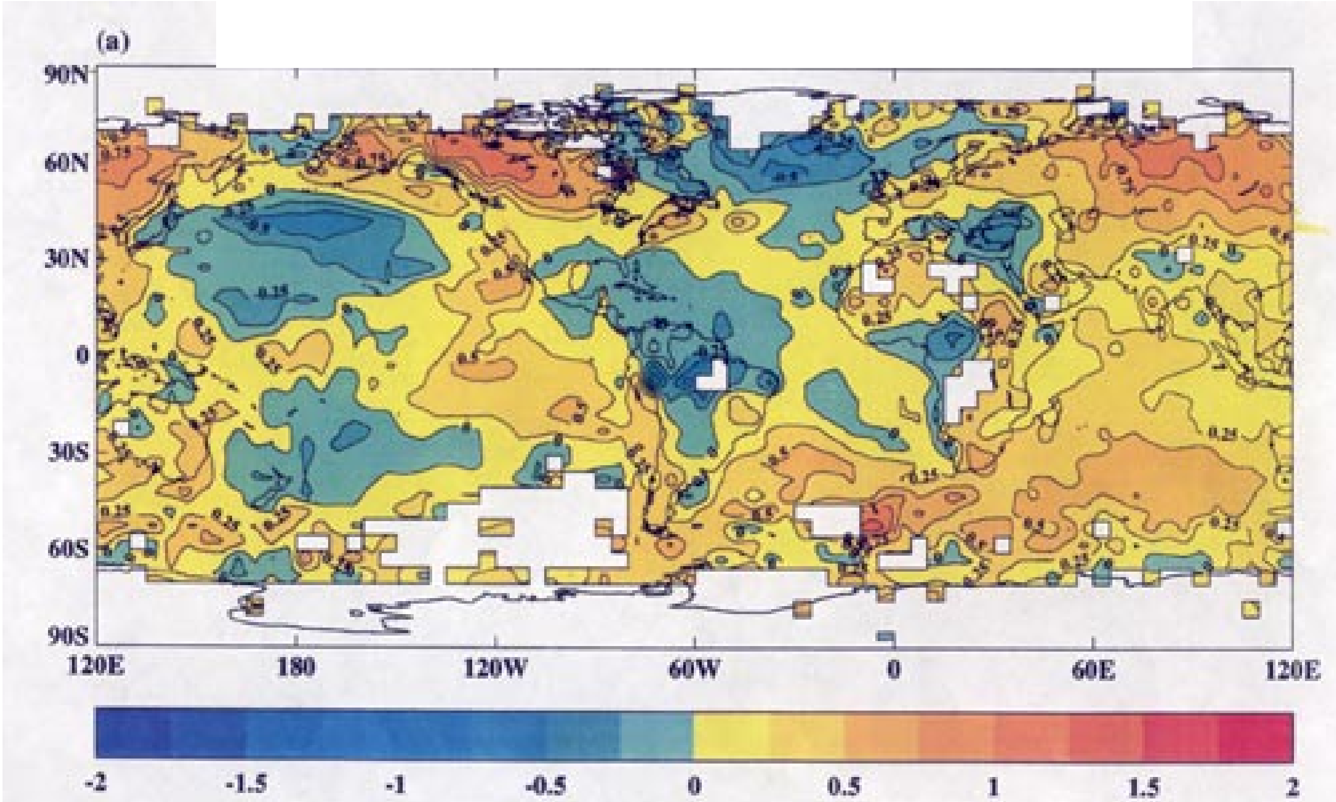


PLATE 5 Annual surface temperature in °C for 1975 to 1994 relative to 1955 to 1974. SOURCE: IPCC (1996). Courtesy of the Intergovernmental Panel on Climate Change (IPCC).

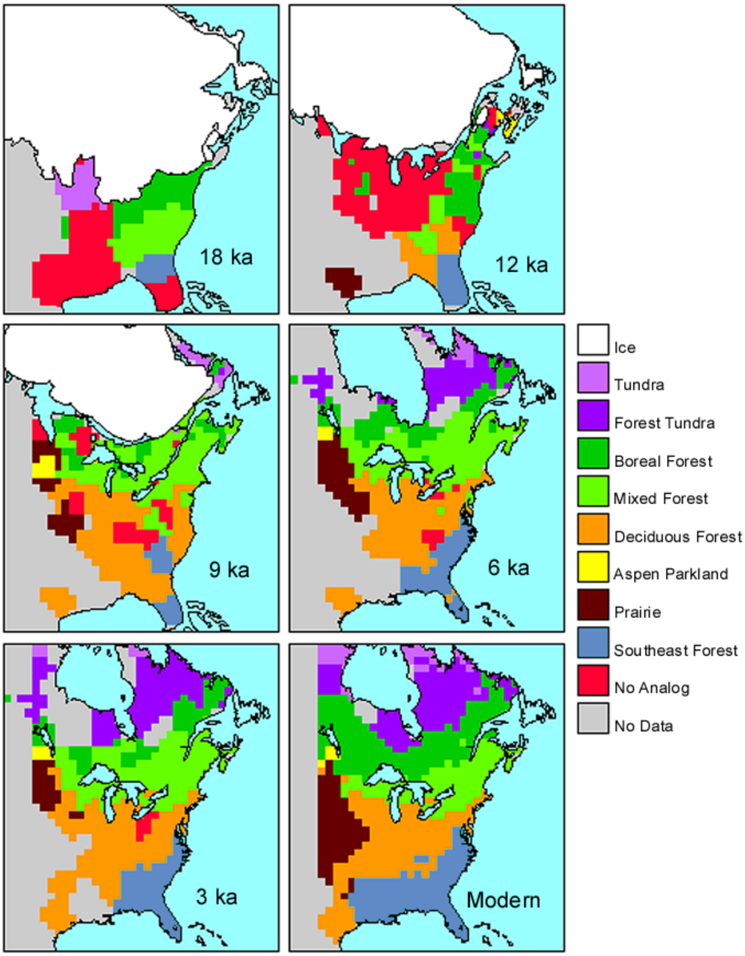


PLATE 6 Selected paleovegetation maps for 18,000 years ago (18 ka) through modern times, reconstructed using the method of modern analogs and over 13,000 samples of fossil and modern pollen (Webb et al., 1991; Overpeck et al., 1992). No vegetation is mapped in areas without fossil pollen data; "no analog" refers to vegetation without any modern analog. SOURCE: Overpeck et al. (1992). Courtesy of the Geological Society of America.

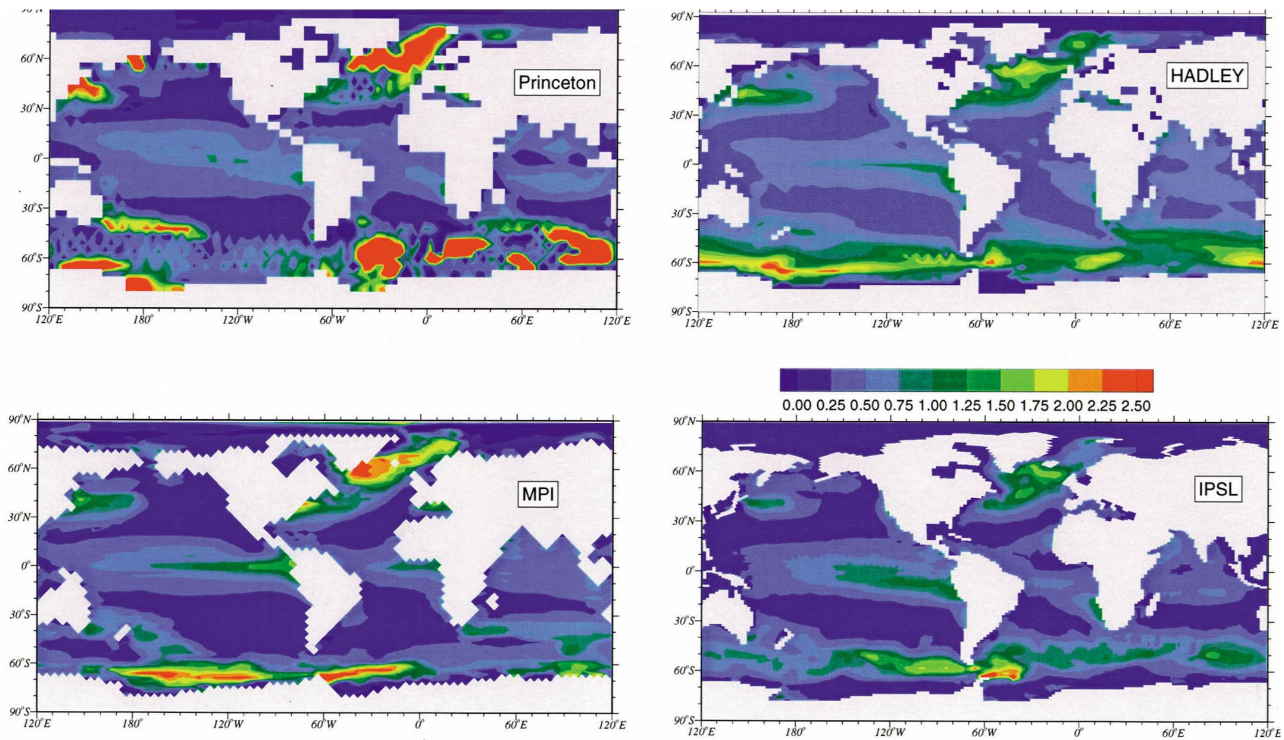


PLATE 7 Air-sea δCO_2 flux (1990) [mol m^2 yr^{-1}]. Oceanic uptake of anthropogenic CO_2 by four different models; global spatial distribution. Results show that, although the models all have the same overall pattern of enhanced uptake in upwelling and convective regions and weak uptake in downwelling regions, there are dramatic regional differences, particularly in the Southern Ocean. Courtesy of the IGBP/GAIM Ocean Carbon Modeling Intercomparison Project.

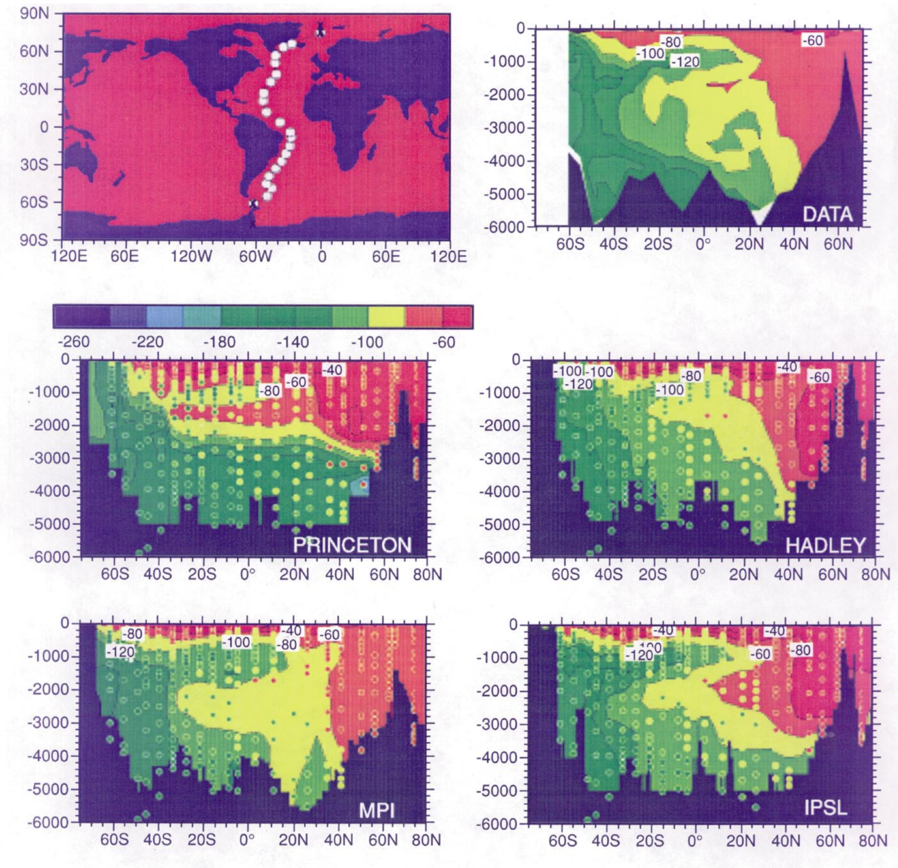


PLATE 8 Vertical distribution of natural radiocarbon along a section in the West Atlantic, as simulated in four ocean models and as observed in a 1973 GEOSECS transect (top left). The units are in $\delta^{14}C$. Courtesy of the IGBP/GAIM Ocean Carbon Modeling Intercomparison Project.