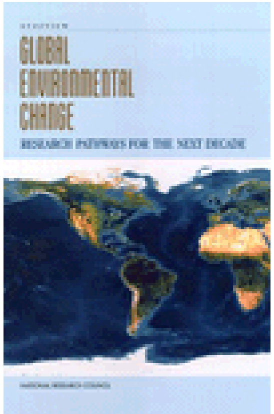

Global Environmental Change: Research Pathways for the Next Decade, Overview

Committee on Global Change Research, National Research Council

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OVERVIEW

Global Environmental Change: Research Pathways for the Next Decade

Committee on Global Change Research
Board on Sustainable Development
Policy Division

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Preface

In the coming century, a human population perhaps twice as large as the population today 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 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 *Overview* volume, the Committee on Global Change Research (CGCR) provides guidance on such a framework by clarifying especially promising pathways for the planning of future US research on global environmental change. This document summarizes the background and the findings and recommendations presented in the Committee's full report, which will be released in the coming months. The foundation of the report's recommendations includes the accumulated knowledge of worldwide scientific research over the past decade and especially that of the US 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 US 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 US Administration policy and agreements at the Kyoto conference, are not the causes of global change sufficiently clear, and therefore should not the US Global Change Research Program 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 US 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; how ever, there remain many scientific uncertainties about important aspects of climate change. If the United States were to abandon or significantly reduce the 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 are also 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 these systems.

However, a great deal more needs to be understood 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 upon 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 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 also has 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 that 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 last 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.

Therefore, it is time to shift course; we are no longer simply building a ship but steering it too. Given all that we know, these corrections in course 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 focusing 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 our 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 (OMB) 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 *Overview* volume and its Appendix C and elaborated in detail in the full report. The recommendations in these documents 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 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 it 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 Department of Defense, and their international partners. To further the advances of the first three polar platforms, the Committee calls for restructuring NASA's Earth Observing System 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 innovation.

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 sound scientific and intellectual strategy for the transition of our nation and indeed our global society to a sustainable future. This CGCR report will help to guide the Board'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 to sustainability.

ACKNOWLEDGMENTS

A study like this one, of such broad coverage, would not have been possible without assistance from many notable experts (see Committee Roster). In addition to the persons listed, 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 Global Ocean-Atmosphere-Land System, Climate Variability on Decade-to-Century Time Scales, 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

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EDWARD A. FRIEMAN, *Chairman*
Board on Sustainable Development
BERRIEN MOORE III, *Chairman*
Committee on Global Change Research

OVERVIEW

Global Environmental Change: Research Pathways for the Next Decade

SUMMARY

During its first 10 years of operation, the United States 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 our nation 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

The 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—prompted the US 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 due to 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 US National Climate Program and the World Climate Program.[1]

> *"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." NRC, 1983a*

In parallel, beginning in the mid-1970s, the US 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]

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

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. The priorities and nature of this program, from a US 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.

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 (EOS) to provide long-term global observations, with an empha sis 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 Association (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 these 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 19th century and became a widely accepted idea by the beginning of the 20th 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 taken first 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 US Government. Subsequently, beginning in the late 1960s, early computer model simulations started to explore the possible changes in temperature and precipitation that could occur due to 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 will result and no reason to believe that these changes will 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 due to 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 last 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 has simultaneously considered climate change and variability within the broader context of global change. The Committee on Global Change Research (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 (MTPE/EOS), 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—the 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 US research and assessment program was launched, and the NRC was commissioned to conduct a series of studies.[21] But soon, Rowland and Molina 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 of Rowland and Molina[a] 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 initiated 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

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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 chlorofluorocarbon 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.

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, 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
- Human Dimensions of Global Environmental Change

Pathways (see Appendix B) 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 environment, 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 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 (see Appendix C). Four to six Research Imperatives are identified for each topical area. Sometimes these imperatives closely interconnect. The Research Imperatives provide the 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 measurements networks in a matter of minutes through a series of telecommunication 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 Bib liography). 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] which was 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 follow:

- 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
- 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, 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 US-French Topex-Poseidon mission have advanced our knowledge of sea surface change and ocean circulation. The Mission to Planet Earth Pathfinder data sets 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 last 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 that 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 data sets, 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% supports space-based observation programs, and 39% 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 1996–97 in the 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 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%) 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%). As indicated above, this distribution of resources essentially continues in the fiscal year 1998 budget. It can be argued that the large investment required to develop and deploy the space observation component of USGCRP has comprised perhaps too large a fraction of the "focused" budget of the USGCRP. 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.

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[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 page ii in *Our Changing Planet: The FY 1998 U.S. Global Change Research Program.*

[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 efficiencies, encourages rational resource allocation, and allows examination of key scientific questions requiring a long-term approach . . . " NRC, 1995*

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 it 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 US 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 in 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% of USGCRP observations were devoted to in-situ measurements.) Finally, although major breakthroughs have emerged from the research and analysis 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 of lowering their cost, while also making the space-based systems more budgetarily robust and flexible. We applaud NASA's Earth System Science Path finders 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: research and analysis 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 recently 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 present (1997–98) 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 present 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 last 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 the coordination among 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 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

[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 of the full Report.

of CFCs have also enabled the tracing of atmospheric and oceanic circulations as well as improving the understanding of stratospheric ozone loss. Precise measurements of solar radiance have helped us to distinguish between natural and human influences on global mean temperature.

The general lesson here, then, is that high-quality data is an immensely powerful lever to obtain scientific insights on global change.

Need for a Focused Scientific Strategy

NRC reviews of the USGCRP over the past decade (see Bibliography), 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. *Pathways* strongly reiterates this 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 hydrologic 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 within the international community, must recognize the importance of providing scientific leadership in defining and diagnosing the 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 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.

FINDINGS AND RECOMMENDATIONS

The CGCR is charged with providing scientific advice to the federal government on how the United States should execute global change research. *Pathways* addresses this task and the challenge of defining a new strategy for the 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 the 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 required to manage these observations as well as some of the fundamental modeling issues that must be addressed to link the observations with the questions. Appendix C summarizes the Research Imperatives and primary Scientific Questions to which the United States research effort should be directed.

RESEARCH IMPERATIVES AND SCIENTIFIC QUESTIONS—DRIVERS OF OBSERVATION AND RESEARCH

The Research Imperatives, which have been 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 ENSO/TOGA 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.

The fundamental scientific progress of 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 (see Appendix C) 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.
- 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 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 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 systems and the mechanisms responsible for the exchange and distribution between and within those systems.
- 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 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 are the natural limits 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 were the causes 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 ecosystems, 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 (see Appendix C). 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 to document change.

An additional finding flows from the full 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 US 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[g] program demonstrates that it is beginning to be addressed better internationally.

[g]Established in 1991, DIVERSITAS is jointly sponsored by 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 International Geosphere-Biosphere Program) and by the UN 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 build a worldwide capacity for the science of biodiversity.

CROSSCUTTING THEMES

Two common, linked themes emerge clearly from the identified Research Imperatives, Scientific Questions, and the associated observations (elaborated in Appendix C and described in the full report):

- The water and carbon cycles
- 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.[h]

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 upon the progress made by the Global Energy and Water Experiment (GEWEX) in the World Climate Research Program and the Biospheric Aspects of the Hydrological Cycle (BAHC) project of the International Geosphere-Biosphere Program.

Elucidating the climate system and possible anthropogenic changes, in addition to natural variability, are paramount goals 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.

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 is a central responsibility of the US 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,

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Carbon monoxide is not a greenhouse gas, but it is involved with the chemistry of other greenhouse gases (e.g., carbon dioxide and methane).

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 (elaborated in Appendix C and discussed in the full report). 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
- 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-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 to identify preliminary emphases for required observations and data systems and to 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 out lined, 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.[i] 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 constraints 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.

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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.

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 and 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 NOAA's NPOESS program with NASA's Earth Observing System 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 we recognize 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 necessary 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 address 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 DOD role and influence on the observational, space-based monitoring program must be addressed by USGCRP.

TECHNICAL INNOVATION

Innovation is essential for scientific progress in this 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 been 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 technologies.

Technological advances in small satellite systems, robotics, micro-electronics, 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 R&Acomponent of the national research effort must be recognized for its central contributions to science, public policy, and understanding of human-dimensions issues.

DATA SYSTEMS

The issue of data systems and the design of those systems 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 and 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 principle 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 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 3 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 as well as the software is undergoing fundamental changes. Although the scientific community has logically paid attention mainly to such government and academic backbones as vBNS and Internet-2, the more important shift is occurring in the widespread distribution of high bandwidth (1-10 Mbps) to the home. 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 NSF 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 our 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 by the agencies that support this research with public funds.

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 initiallevel processing and long-term archiving and that charges 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.[j]

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 on-line 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.

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 policy action. The last requirement implies provision of some prognostic infor

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The "federation" concept was recommended in a 1995 NAS Review of the USGCRP and refers to a federation of partners selected through a competitive process and open to all.

mation. 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, 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 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.

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 Bibliography contains many examples.
6. ESSC, 1986, 1988.
7. Goody, 1982.
8. NRC, 1986.
9. ESSC, 1986, 1988
10. Revelle, R., and H. E. Suess, 1957.
11. MIT, 1970, 1971.
12. NRC, 1982a.
13. NRC, 1979.
14. NRC, 1979.
15. NRC, 1982b, 1991.
16. WMO, 1979, 1990.
17. WMO, 1984, 1986.
18. IPCC, 1995.
19. NRC, 1995.
20. NRC, 1996.
21. e.g., 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. USGCRP, 1997, p. 78.

28. USGCRP, 1995, p. 109.

29. NRC, 1995.

30. 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.

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APPENDIXES

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 cha 1%>> search activities of the United States with such activities of other nations and international organization, 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 recommended 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 At 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

GLOBAL ENVIRONMENTAL CHANGE: RESEARCH PATHWAYS FOR THE NEXT DECADE

APPENDIX C

RESEARCH IMPERATIVES AND SCIENTIFIC QUESTIONS

A research framework across the wide scope of global environmental change is outlined in the full report, "*Global Environmental Change: Research Pathways for the Next Decade,*" in terms of the primary topical areas (biology and biogeochemistry of ecosystems, climate system on seasonal to interannual time scales, climate system on decadal to century timescales, chemistry of the atmosphere, paleoclimate, and human dimensions of global change). Research Imperatives are central scientific issues posed to each of the six primary topical areas by the challenge of global environmental change. Each Research Imperative is elaborated by a set of Scientific Questions. These are summarized from the full report and provided below.

Biology and Biogeochemistry of Ecosystems

Land-Surface and Climate Imperative

Understand the relationships between land-surface processes, including land-cover change, climate, and weather prediction.

Land-Surface and Climate Questions

- 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 may 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?

Biogeochemistry Imperative

Understand the changing global biogeochemical cycles of carbon and nitrogen.

Biogeochemistry Questions

- How is terrestrial carbon storage regulated by land use, changes to marine ecosystems, internal ecosystem processes, and climate, and how may 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 carbon dioxide, 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?
- 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 nitrogen 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?
- 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 role do sulfur and organic compounds from biogenic sources, dust from agriculture and other soil disturbances, and biomass burning play in global aerosol forcing?

Multiple Stresses Imperative
Understand the responses of ecosystems to multiple stresses.
Multiple Stresses Questions

- 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?
- What are the required data sets, theory, and models needed to understand the 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?

- 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

Understand the relationship between changing biological diversity and ecosystem function.

Biodiversity Questions

- 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?

Seasonal to Interannual Climate Change

El Niño–Southern Oscillation (ENSO) Imperative

Maintain and improve the capability to make ENSO predictions.

ENSO Questions

- What is the inherent limit of ENSO predictability? How can this limit be determined? What limits the skill of ENSO predictions now?

- What mix of observations is needed to initialize forecasts to optimize the skill of ENSO predictions? How can this mix be determined?
- Which are the proper measures of the skill of ENSO prediction?
- How does decadal variability in the Pacific affect the prediction of ENSO?
- Through what mechanisms do seasonal to interannual tropical Pacific variations influence the midlatitudes?
- 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?
- What is the effect of regions outside the tropical Pacific on the prediction of ENSO variations?

Global Monsoon Imperative

Define global seasonal to interannual variability, especially the global monsoon systems, and understand the extent to which it is predictable.

Global Monsoon Questions

- 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?
- 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?
- What are the roles of slowly varying conditions at the Earth's surface [sea ice, sea surface temperature (SST), snow cover, and soil moisture] in determining the nature of interannual variation in the global atmosphere?
- 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?
- What is the role of ENSO in creating variability in the monsoon climates of the world, and vice versa?
- Is there variability of the monsoon that is independent of ENSO, and is it predictable?
- 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?
- 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?

Land-Surface Exchanges Imperative

Understand the roles of land-surface energy and water exchanges and their correct representation in models for seasonal to interannual prediction.

Land-Surface Exchanges Questions

- 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?
- What representation of runoff is best to calculate evapotranspiration in seasonal to interannual climate prediction models?
- 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 measurement and tradeoffs? How can they be obtained and how can models be formulated to accept them?
- How can we use observations of the seasonal to interannual variations in biogeochemical cycles and ecosystem properties to infer the underlying dynamics determining these variations?
- What is the role of high-latitude feedbacks between snow cover extent, stream flow, and seasonal to interannual variability, and to what extent are these processes adequately modeled?

Downscaling Imperative

Improve the ability to interpret the effects of large-scale climate variability on a local scale (downscale).

Downscaling Questions

- In what ways can local climate variance be explained in terms of large-scale climate variability?
- What local climate variables need to be upscaled to ensure adequate coupling of local climate to large-scale climate?

Terrestrial Hydrology Imperative

Understand the seasonal to interannual factors that influence land-surface manifestations of the hydrological cycle, such as floods, droughts, and other extreme weather.

Terrestrial Hydrology Questions

- What are the implications of seasonal to interannual climate forecasts for flood prediction?
- What are the implications of seasonal to interannual climate forecasts for drought prediction and forecasting?
- What are the implications of seasonal to interannual climate forecasts under "normal" climate conditions?

Decadal to Century (Dec-Cen) Climate Change

Climate Patterns Imperative

To understand patterns in the climate system, the following interdependent imperatives exist.

- *Natural Climate:* Improve knowledge of decadal to century-scale natural climate patterns; their distributions in time and space; and 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 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 Patterns Questions

- What is the longevity of climate patterns and their spatial/temporal variance?
- What is the best way of characterizing the known patterns, and are there additional patterns of interest?
- Which patterns represent true dynamic modes, and which are simply statistically consistent structures or geographically forced distributions?
- What mechanisms generate, maintain, and modify the patterns, what is the role of these mechanisms in the spatial propagation of regionally initiated variability and change, and what are their critical dependencies?
- What is the relationship between the observed climate patterns and global warming?

Climate System Components Imperative

Address the issues of those individual climate components whose resolution will most efficiently and significantly advance our understanding of dec-cen climate variability.

Climate System Components Questions

Atmosphere

- How much of the dec-cen variability is unforced (reflecting nonlinear internal interactions)?
- How does large-scale circulation change on dec-cen timescales, and how does it interact on these scales with regional and higher frequency changes?
- What are the magnitudes, spatial and temporal patterns, and mechanisms of midlatitude atmospheric responses to both midlatitude and tropical SSTs?
- 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?
- 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?

Oceans

- What are the dec-cen patterns of ocean variability, and what dynamical mechanisms govern them at dec-cen timescales?
- 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?
- What are the dec-cen fluctuations of circulation structure and intensity, and water mass pathways, how are they affected by surface forcing, and what are the mechanisms of the fluctuations?
- What feedback and coupling mechanisms maintain SST, heat, freshwater, sea ice, and chemical anomalies on dec-cen timescales?
- What are the mechanisms of region-to-region and basin-to basin interaction on dec-cen timescales?
- How is carbon partitioned in the ocean, and what are the roles of physical processes in the carbon flux?

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?
- What mechanisms underlie dec-cen patterns of interaction between the sea ice and snow fields and the atmosphere, ocean, and land systems?
- Through what mechanisms are changes in the cryosphere of the polar regions linked or teleconnected to midlatitude and tropical regions?
- What is the history and current global budget of land-locked ice and snow, and what are the primary mechanisms controlling this budget?

Land and Vegetation

- What are the effects of human activity and climate change on ecosystem structure and function?
- What are the relative contributions of the different processes by which vegetation and soils store or lose carbon?
- What are the expected future emissions of methane, nitrous oxide, and volatile organic carbon compounds by soils and vegetation?
- How do dec-cen changes in land use and land cover affect land-surface energy balance on dec-cen time scales?
- How does vegetation influence the transfer of freshwater through the land surface on dec-cen timescales?
- How do changes in vegetation cover influence the loading and composition of atmospheric aerosols on dec-cen timescales?

Hydrologic Cycle

- What are the patterns and mechanisms of prolonged drought on dec-cen timescales found in paleoclimatic records?
- How do the distributions of water vapor, precipitation, and clouds interact with surface boundary conditions and changes on dec-cen timescales?
- By what combination of remote and in-situ observations can we measure the large-scale distribution of precipitation on dec-cen timescales?
- What are the spatial and temporal changes in land storage of water and the pathways and fluxes of land water to the oceans?
- What are the patterns and mechanisms of the dec-cen droughts measured over the last several hundred years?

Atmospheric Composition and Radiation Budget

- What are the changes in the spatial distribution of carbon storage and flux on dec-cen timescales?
- How do mixed-layer water replacement rates interact with biological processes to produce changes in ocean carbon storage?

- What are the uptake, pathways, and fate of anthropogenic carbon in the ocean on dec-cen timescales?
- What are the contributions of various sources and sinks to the recent increase in methane?
- How does photochemical breakdown of methane contribute to other chemical and radiative processes in the atmosphere on dec-cen timescales?
- Why is nitrous oxide increasing on dec-cen timescales?
- Why has tropospheric ozone increased since the last century, and are further increases likely?
- How does the coupling between chemistry, dynamics, and radiation in the lower stratosphere and upper troposphere operate on dec-cen timescales?
- 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 proxies for solar activity (e.g., sunspots, cosmogenic nuclides) relate to total solar irradiance on 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?
- What feedbacks govern climate and ecosystem responses to spectral changes in solar irradiance on dec-cen timescales?

Chemistry of the Atmosphere

Stratospheric Ozone and Ultraviolet Radiation Imperative

Define and predict secular trends in the intensity of ultraviolet exposure 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.

Stratospheric Ozone and Ultraviolet Radiation Questions

- Will the 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?
- 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; can we develop models to correctly simulate this evolution?

- What is the role of the largely unexplored tropical region of the stratosphere in global ozone change?
- What are the interactions between stratospheric ozone depletion and climate change?
- What are the consequences of current and future perturbations, such as aircraft emissions and volcanic eruptions, on stratospheric ozone concentrations?

Atmospheric Greenhouse Gases Imperative

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.

Atmospheric Greenhouse Gases Questions

- What are the regional sources and sinks of carbon dioxide other than fossil fuel burning?
- How large are the individual methane sources?
- What are the missing sources of nitrous oxide?
- What causes year-to-year changes in the trends of the greenhouse gases?
- How are the carbon dioxide increases correlated with oxygen decreases as a function of altitude, latitude, longitude, and season?
- Are the Montreal Protocols and successor agreements effective in mitigating the climatic warming from chlorofluorocarbons and hydrochlorofluorocarbons? Which new halogenated compounds may affect climate in the future?
- What are the trends in ozone in the troposphere and stratosphere, and what are the causes of these trends?
- 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?
- What are the trends in water vapor in the upper troposphere and lower stratosphere, and what are the causes of these trends?

Photochemical Oxidants Imperative

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. Develop a better understanding of what determines the ability of the atmosphere to cleanse itself of pollutants, both now and in the coming decades.

Photochemical Oxidants Questions

- To what extent does our current understanding satisfactorily explain simultaneous measurements of hydroxide concentrations and the principal hydroxide chemical production and loss processes?
- Can the oxidation of compounds or appearance of their oxidation products be successfully used to infer representative concentrations of hydroxide, whether seasonally and regionally or annually and globally?
- To what extent do other oxidants (nitric oxide, hydrogen peroxide, halogen atoms, etc.) play significant roles?
- To what extent do changes in stratospheric ozone, climate, and/or cloud cover affect the oxidizing capacity of the lower atmosphere?
- What determines the distribution of ozone in the troposphere and how is the distribution likely to change in the coming decades? More specifically—
- What fraction of tropospheric ozone can be attributed to transport from the stratosphere and how does this change with meteorology and season?
- What portion of ozone 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)?
- What is the contribution of urban pollution to rural and regional ozone, and conversely, what is the impact of rural and regional ozone on urban pollution?
- How does meteorological variability affect the trends of ozone and/or its precursors?
- What are the major sources of nitrogen oxides in each region of the atmosphere over various geographic regions? What are the rates of nitrogen oxide and nitrogen dioxide (NO_x) emissions from these sources?
- Which major reservoir and oxidizing species and which gas-phase and heterogeneous chemical processes are responsible for the partitioning within the NO_x family?
- Where and when is the production of ozone limited by the availability of volatile organic compounds (VOC) or nitric oxide?
- What are the trends in regional and local ozone precursors (NO_x, VOC, carbon monoxide)?
- What design and implementation strategies will provide monitoring networks capable of determining, whether control measures for photochemical oxidants are having the intended impact?
- What design and implementation strategies will yield monitoring networks capable of determining, for a particular air qua 28%>> oblem, 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)?

Atmospheric Modeling Imperative

Improve atmospheric models to better represent current atmospheric oxidants and predict the atmosphere's response to future levels of pollutants.

Atmospheric Modeling Questions

- What laboratory research is required to understand the fundamental chemical processes (heterogeneous and homogeneous) involved in tropospheric oxidant formation?
- What atmospheric measurements are required, and of what precision and accuracy, to evaluate and apply diagnostic and predictive models of tropospheric oxidant chemistry?
- What are the quantitative certainties associated with the estimates from diagnostic and predictive models of tropospheric oxidant chemistry?
- 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)?

Atmospheric Aerosols and Ultraviolet Radiation Imperative

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.

Atmospheric Aerosols and Ultraviolet Radiation Questions

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

Toxics and Nutrients Imperative

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.

Toxics and Nutrients Questions

- How are interactions between the atmosphere and biosphere influenced by changing atmospheric concentrations and by the deposition of harmful and beneficial compounds?
- 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?

Paleoclimate

Paleoclimate Imperatives

Document how the global climate and 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 are the natural limits 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 controlling and will control climate change on societal timescales (season to century). Determine what were the causes of the rapid climate change events and rapid transitions in climate state.

Paleoclimate Questions Stream One—The Last 2000 Years

- Is the warming experienced during the 20th century unusual?
- Are there major modes of subdecadal, decadal, and centennial scale variability?
- Do certain regions on Earth play leading roles in climate change by either driving or responding to climate change (e.g., North Atlantic, Southern Ocean, tropics)?
- Are climate change events (e.g., Little Ice Age, Medieval Warm Period) synchronous in magnitude and timing in both hemispheres or do some display regional differences?
- Have major atmospheric circulation systems such as ENSO, Asian-Aus

tralian-African monsoon, 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 a response to changes in boundary conditions (e.g., sea-surface temperature, Tibetan snow cover, clouds)?
- Are there teleconnections in the atmospheric circulation systems of both hemispheres that lead to parallel records of climate change on dec-cen timescales?
- How has the hydrology of the planet changed over the last two millennia?
- How has the record of ENSO and its climate teleconnections changed over the last two millennia?
- How has the record of explosive volcanism changed over the last 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 last 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 last two millennia? How do ice sheets, mountain glaciers, and other changes in the hydrologic cycle contribute to this change?
- How have ecosystems (e.g., equatorial rain forests, tundra, forest, steppe, glacial) responded to environmental change over the last two millennia?
- How has human activity impacted the environment?
- How have humans responded to environmental change?

Paleoclimate Questions Stream Two—The Last 250,000 Years

- Are there major modes of centennial-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 found also 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, intertropical convergence zone, and jet streams?

- How are hydrologic changes in the tropics related to climate change in extratropical regions? What causes these hydrologic 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?

Human Dimensions of Global Change

Human Dimensions Imperatives

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 ecosystems, 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, and institutions and economic and technological transformations.

Human Dimensions Questions

What Is the Role of Consumption in Causing Global Change?

- 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 highly 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 issues such 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?

What Are the Social Driving Forces for Land-Use and Land-Cover Change?

- What comparative case studies of land-use and land-cover change are useful for the modeling of land-use change at regional and global scales?
- Which human activities (e.g., patterns of land use and management, chemical releases) can significantly alter the potential for major environmental surprises?

How Does Technological Transformation Influence Global Change?

- What factors determine variations among sectors and actors and change over time in the approximately 1% 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 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?

What Are the Regional Vulnerabilities to, and Consequences of, Global Change?

- What are the sectoral impacts of regionally relevant climate change assessments and seasonal to interannual climate predictions?
- 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?
- 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?
- How can we improve geographic links to existing social and health data?

What Are the Most Effective Responses to Global Change?

- How can society deal with the possibility that citizens will become immobilized by warnings of possible, but highly improbable, environmental catastrophes?
- What are the characteristics of effective institutions for managing global environmental change?
- What are the correlates of effectiveness for international regimes and institutions and for management of international environmental and natural resource issues, particularly regarding the 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?
- What are the links among land-use change, migration, political and economic changes, cultural factors, and household decision making?
- Understanding the interrelations between migration and environmental change.

What Methods Can Be Used to Improve Decision Making About Global Change?

- Are there ways to improve the economic assessments of the costs, benefits, and distributional effects of forecasted climate changes and variations, taking adaptive capacity into account?
- 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?
- 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 it can be more easily 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 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?
- How can the integration of human dimensions research within the USGCRP and other international research programs be improved?

APPENDIX D

ACRONYMS

CFCs	Chlorofluorocarbons
CGCR	Committee on Global Change Research
CENR	Committee on Environment and Natural Resources
DOD	Department of Defense
DOE	Department of Energy
ENSO	El Niño–Southern Oscillation
EOS	Earth Observing System
ESSC	Earth System Sciences Committee
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
ICSU	International Council of Scientific Unions
IGBP	International Geosphere-Biosphere Program
MetOp	Meteorological Operational (Satellite)
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-Orbiting Operational Environmental Satellite System
NRC	National Research Council
NSF	National Science Foundation
NSTC	National Science and Technology Council
OMB	Office of Management and Budget
R&A	Research and Analysis
TOGA	Tropical Oceans and Global Atmosphere
USGCRP	US Global Change Research Program
WMO	World Meteorological Organization