

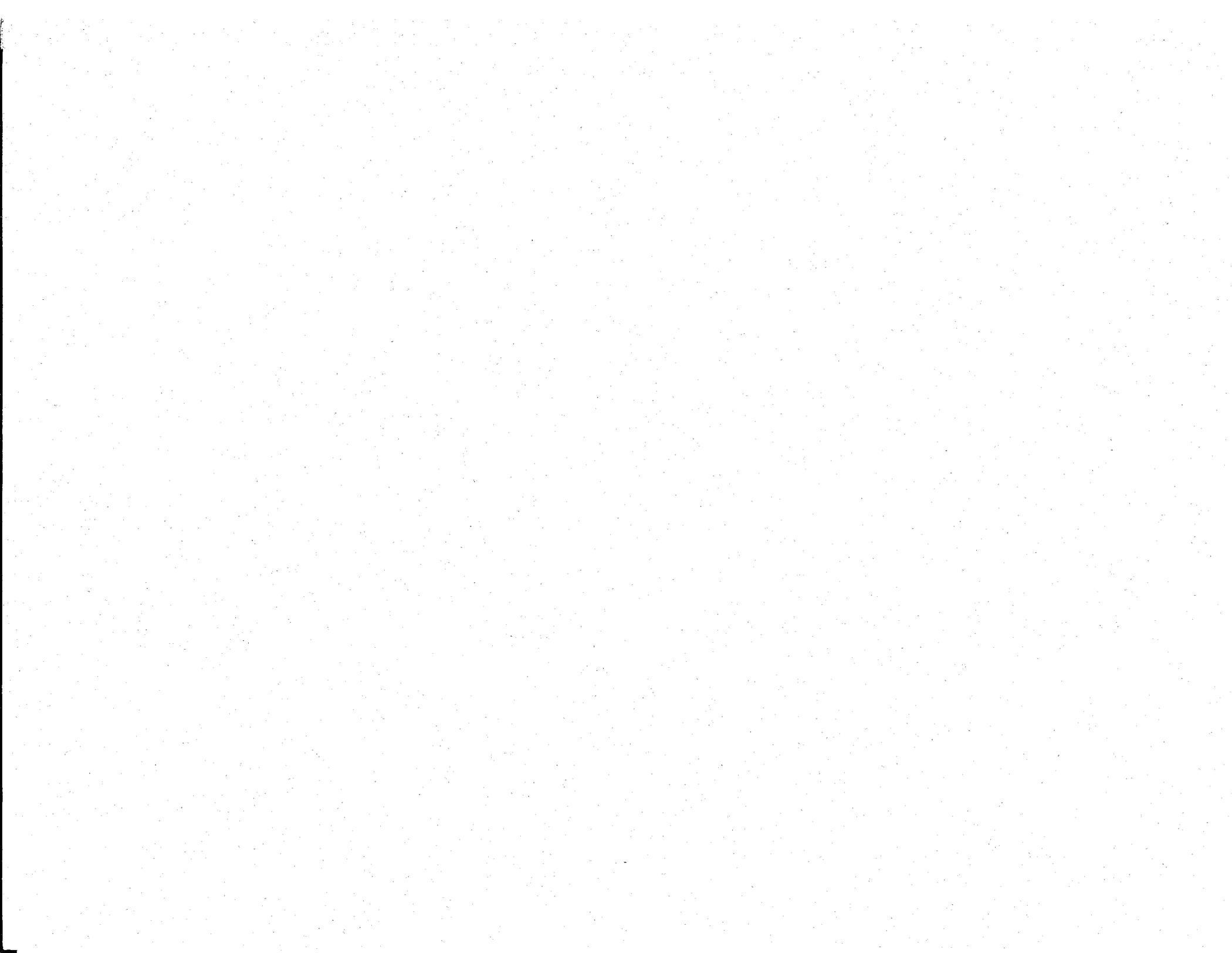
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**A Review of
the U.S. Global Change
Research Program
and
NASA's
Mission to Planet Earth/
Earth Observing System**

NATIONAL RESEARCH COUNCIL



**A Review of
the U.S. Global Change
Research Program
and
NASA's
Mission to Planet Earth/
Earth Observing System**

**Committee on Global Change Research
Board on Sustainable Development
Policy Division
National Research Council**

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Preface

This report reflects the results of a ten-day workshop convened at the Scripps Institution of Oceanography July 19-28, 1995. The workshop was convened as the first phase of a two-part review of the U.S. Global Change Research Program (USGCRP), which is being conducted in response to

1. the long-standing commitment of the National Research Council (NRC) to providing scientific guidance and periodic review of the USGCRP and its component programs and plans; and
2. requests from congressional leaders in both the House and the Senate, endorsed by the interagency Subcommittee on Global Change Research, for a timely review of the USGCRP with an early specific focus on the NASA Mission to Planet Earth (MTPE) and Earth Observing System (EOS) programs in the light of budgetary pressures.

Responsibility for the review of the USGCRP was assigned to the Board on Sustainable Development (BSD) and its Committee on Global Change Research (CGCR). The July workshop was designed to accomplish the first phase of the review -- to conduct an initial assessment of the scientific progress to date in the USGCRP -- and, in the context of that scientific assessment, review the specific role of NASA's Mission to Planet Earth/Earth Observing System (MTPE/EOS) program.

As phase one of the review, the workshop was organized to provide

- a review of the scientific foundations and progress to date in the US. Global Change Research Program and an assessment of the implications of new scientific insights for future USGCRP and MTPE/EOS activities;
- a review of the role of NASA's MTPE/EOS program in the USGCRP observational strategy;

- a review of the EOS Data and Information System (EOSDIS) as a component of USGCRP data management activities; and
- an assessment of whether recent developments in the following areas lead to a need to readjust MTPE/EOS plans. Specific consideration was given to
 - proposed convergence of U.S. environmental satellite systems and programs,
 - evolving international plans for Earth observation systems,
 - advances in technology, and
 - potential expansion of the role of the private sector.

While we believe that this initial emphasis on MTPE/EOS was appropriate in light of the need to be responsive to specific congressional interests, we recognize that, as a result, the July workshop could not adequately address the full spectrum of issues important to a review of the U.S. Global Change Research Program. For example, in consultation with the federal agencies participating in the USGCRP, the initial scientific assessment of the program was organized around four key scientific areas: (1) seasonal to interannual climate prediction, (2) atmospheric chemistry; (3) ecosystems; and (4) decadal to centennial climate change. Taken together, these four science areas reflect the continuing evolution of global change research into higher levels of intellectual and programmatic integration. Although these four areas represent the appropriate principal scientific foci for the USGCRP, the program's progress must also be evaluated in the individual Earth science disciplines that provide the foundation for an increasingly integrated view of the Earth system. Some of these disciplinary areas, such as climate and hydrological systems, biogeochemical cycles, and ecological systems and dynamics, received focused attention at the workshop. A detailed look at others, such as Earth system history, solar influences, and solid Earth processes, was deferred until the second phase of the review.

Research into the human dimensions of global change is a special case that deserves specific mention here. The workshop was designed with an explicit understanding that an effective program of research in all four of the principal science areas requires the integration of physical, natural, and social and economic sciences. Unfortunately, representation from the social science and economics research communities was limited during the workshop. As a result, we plan to include an explicit focus on the human dimensions of global change during the second phase of the review.

The present report summarizes the findings and recommendations developed by the Committee on Global Change Research on the basis of the presentations, background materials, working group deliberations, and plenary discussions of the workshop. A majority of the members of the committee participated in the La Jolla workshop. The report was subsequently reviewed in detail by the full membership of the CGCR, and the final text reflects extensive com-

ments and modifications by the committee members. The committee believes these conclusions to be representative of the consensus of the workshop; however, their specific content is the responsibility of the committee alone.

In addition, we have appended summaries prepared by the six working groups convened in the course of the workshop (Appendixes A-F). These documents were written by the designated working group chairs and reflect their sense of the views of working group participants, further illuminated by extensive plenary discussions in the course of the workshop. These documents provide a window into the information, analysis, and discussion drawn upon by the committee in formulating its conclusions. The chairs of the six working groups are also preparing a set of more complete interim working documents that describe their deliberations in more detail and will be used as critical input to the second phase of the comprehensive review of the USGCRP.

The July workshop constituted the first step in a broader review of the USGCRP as a whole that will be concluded at a meeting of the Committee on Global Change Research in the late fall or early winter of 1995. In light of the issues raised at the workshop, we anticipate that this meeting will provide an opportunity to address a number of remaining issues, including

- completion of a review of the USGCRP scientific accomplishments and priorities, including a more detailed look at disciplinary areas not fully addressed during the workshop;
- an in-depth look at the roles and responsibilities of the participating agencies and further discussion of interagency program management issues;
- an evaluation of USGCRP programs and plans in the areas of integrated observations, information management (including EOSDIS), process studies, modeling and prediction, and assessment;
- further discussion of the development of an integrated observational strategy for the USGCRP, including analysis of the opportunities and requirements associated with the planned convergence of Department of Defense (DoD) and civilian meteorological satellite programs;
- a review of USGCRP contributions to international global change research programs including the World Climate Research Program, the International Geosphere-Biosphere Program, and the Human Dimensions of Global Change Program; and
- the practical applications of the results of USGCRP research and an assessment of the program's effectiveness in meeting the needs of decision makers in the public and private sectors.

The Committee on Global Change Research will then prepare a comprehensive review of the U.S. Global Change Research Program for release early in 1996.

The workshop brought together a broadly constituted group including members of the Committee on Global Change Research and the Board on Sustainable Development; chairs or representatives of other relevant NRC units concerned with elements of the USGCRP; leaders of the major international global change research programs; and other invited scientists and technologists from academia and industry selected for their expertise and experience in relevant technical areas. In order to ensure the required level of expertise, scientists currently active in the USGCRP and supported by the agencies participating in the program were invited to take part. We also want to point out that some members of the Committee on Global Change Research also receive funding from USGCRP agencies. However, to foster a balanced and objective review, the workshop also included experts outside the USGCRP research community, as well as individuals who have been critical of the USGCRP and of NASA's MTPE/EOS program in the past. The workshop also benefited from the presence of representatives of USGCRP agencies (Appendix G). These representatives were invited to make formal presentations and to serve as liaisons to provide workshop participants with the background information and programmatic details required to support their deliberations. We appreciate greatly their contributions of time, expertise, and experience over the week and a half of the workshop.

As workshop co-chairs, we worked closely with the Subcommittee on Global Change Research of the interagency Committee on Environment and Natural Resources in planning the workshop, to develop appropriate background information, and to identify the appropriate level of agency participation. We are very grateful to the many individual federal officials associated with these organizations for their contributions to this effort.

Finally, we wish to express our appreciation to the NRC staff--John Perry and Claudette Baylor-Fleming of the Board on Sustainable Development and volunteer staff members from other NRC units--Frank Eden, Mary Hope Katsouros, and Anne Linn, who worked long hours to bring this project to fruition. In addition, we are grateful for the contributions provided by Eileen Shea of the Center for the Application of Research on the Environment (CARE), who served as study director for this first phase of the USGCRP review and for the La Jolla workshop. We are sure that the many participants share our appreciation of the staff of the Scripps Institution of Oceanography for their unstinting and uniformly effective support of this demanding enterprise.

Berrien Moore III, *Chairman*
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Executive Summary

Assessing accurately the current state of the global environment and increasing our predictive capabilities to aid in anticipating how this environment may evolve are enduring challenges to science. The U.S. Global Change Research Program (USGCRP) seeks to advance scientific understanding of the global environment, assist federal agencies in their missions, and provide reliable information for decision making. The scientific and societal motivations of the program remain compelling, and it should be aggressively pursued.

Future development of the USGCRP should be based on a set of guiding principles:

- **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.**
- **In addition to observational systems and data streams implemented as explicit components of the usgcrp, the program should make use of existing observational systems and data products implemented in support of related environmental monitoring and earth science programs (e.g., the ground-based and satellite observations that support operational weather forecasting).**
- **The USGCRP must utilize advancing technology in addressing these evolving priorities.**
- **An open and accessible program will encourage broad participation by the government, academic, and private sectors.**
- **Success in attacking the long-term scientific challenges of the USGCRP requires an adequate and stable level of funding that promotes management efficiencies and encourages rational resource allocation.**

- Successful implementation of the USGCRP and the realization of its benefits require **informed leadership and collaboration** among the government, academic, and private sectors.

The USGCRP, furthermore, must be implemented as an **integrated** program of observations, process research, modeling, prediction, information management, and assessment. In order to achieve this, **enhanced collaboration and cooperation** are required among the scientific community, the Congress, federal agencies, and the Executive Office of the President to ensure that all elements of the program are considered in the context of the integrated program as a whole.

The program should focus on priority issues in four mature areas of Earth system science that are of great scientific and practical importance. Each area will require the contribution of a variety of traditional Earth science disciplines:

1. **Seasonal to interannual climate prediction:** Improve prediction skills related to El Niño and expand predictive skills beyond the tropics to the extent possible; enhance understanding of land-atmosphere interactions; and establish an international research prototype prediction capability to garner multinational support and to provide benefits to participating countries where usable predictive skill has been demonstrated.
2. **Atmospheric chemistry:** Enhance research and scientific assessment on tropospheric chemistry, including tropospheric ozone and its precursors; characterize global distributions of aerosols; monitor biogenic gases especially over continental areas; and continue monitoring and scientific assessment of ozone in the stratosphere, including links to climate.
3. **Ecosystems:** Improve documentation, assessment, and understanding of the global carbon cycle; investigate the relationships among vegetation, climate, and land use; study the role of managed and natural ecosystems in the exchange of water, carbon dioxide, and biogenic gases; and provide for the inclusion of surface atmosphere processes and ecosystem dynamics in integrative models and scientific assessments.
4. **Decadal to centennial climate:** document, investigate, and assess changes in forcing factors that influence climate; incorporate ocean, land, atmosphere, and ice processes and feedbacks in coupled models; document change through long-term monitoring and assessment of primary climate system characteristics; and investigate economic, technological, and demographic trends that affect the ability of natural and human systems to respond to climate variability and change.

These areas are at different stages of maturity. They have different levels of access to existing remotely sensed data, and each area can make unique contributions to the study of global change. In all these areas, linkages among the physical, natural, and social sciences should be enhanced, and effective U.S. participation in international global change research programs should be encouraged.

Observations of the Earth system play a key role in the USGCRP, and the program requires an integrated observational strategy based on scientific needs, the development and implementation of observing systems appropriate to those needs, scientific guidance, and the application of technological capabilities as appropriate. NASA's Earth Observing System (EOS) should reflect that integrated strategy.

Based on a series of reviews, the program has evolved from its original plans to a reshaped program that is more responsive to the science, more resilient, and more open to the introduction of new technology. There has been a shift from a fixed series of large-vehicle missions to a mixed fleet exploiting small to medium class spacecraft. However, any further structural changes to the near-term EOS missions would cause severe program dislocations. Further budgetary reductions or imposed constraints on technical options could require the elimination of key sensors, slips in schedule, loss of data continuity, and the elimination of advanced technology development that could enhance future research and lower costs.

However, continued evolution is essential. NASA, in concert with the USGCRP community, should consider carefully the observational strategy appropriate for the post-2004 era to ensure that the EOS strategy remains technologically current and scientifically relevant. In the meantime, as a result of technological advances, scientific insights, and programmatic evolution, NASA should move to rebalance the EOS program across space assets, in situ measurements, modeling and process studies, and the data and information management system through a set of feasible and cost-effective actions.

- Maintain a science-driven approach to observational and information management technology.
- Implement the first group of Mission to Planet Earth (MTPE)/Earth Observing System (EOS) components: Landsat-7, AM-1, PM-1, Chemistry-1 (Chem-1), and the Tropical Rainfall Measuring Mission (TRMM).
- Enhance in situ observation programs, process studies, and large-scale modeling activities.
- Develop advanced technologies to reduce the costs of continuing essential observations.
- Focus the tropospheric component of Chem-1 on the global distribution of ozone and its precursors.

- Implement a future framework for MTPE that incorporates advanced instrumentation and vehicle technologies, such as small satellites and remotely piloted vehicles (RPVs), as an integral component of the program, including planning for EOS missions beyond the first group of platforms. Incorporate scientific needs into interagency and international planning for satellite convergence.
- Streamline current the EOSDIS plans for data downlink and Level-0 processing.
- Reconfigure EOSDIS to transfer responsibility for product generation, publication, and user services to a competitively selected federation of partners in government, academia, and the private sector.

The proposed rebalancing of the programs would offer the potential for significant economies, (e.g., by focusing and simplifying the tropospheric component of the Chem-1 mission on ozone and its precursors, by streamlining the data downlink and initial processing of EOSDIS, and by employing a federation of partners in EOSDIS for product generation). The latter two potentially contribute the greatest savings, and the last offers significant new opportunities to research and private sector communities. To ensure scientific success, however, it will be necessary to direct the resources toward (1) expanding in situ observations, process studies, and large-scale modeling; and (2) developing advanced technology to reduce the costs of second- and third-generation missions and to open new scientific opportunities. With integrated, science-driven, and balanced scientific and observational elements, the USGCRP and NASA's MTPE/EOS program can continue to contribute importantly to ensuring our national welfare in a changing global environment.

Introduction

The U.S. Global Change Research Program and its international counterparts were begun to enhance understanding of the global environment and to predict its future evolution. Such collaborative work has long been a hallmark of the Earth and life sciences, in which investigations characteristically transcend the boundaries of classical scientific disciplines and individual nations. Thus, a long history of increasingly ambitious and increasingly integrated scientific programs may be traced, from the polar programs of the late nineteenth century through the International Geophysical Year of 1958 to the Global Atmospheric Research Program, the International Decade of Ocean Exploration, and the International Biology Program of the 1970s.

By the 1980s, a growing body of research, coupled with new views of the Earth from space, reinforced science's vision of our planet as a tightly interconnected and constantly changing system. Public awareness of the links between the current and future state of the global environment and human activities increased during this same period. In combination, scientific insights, technological opportunities, and societal concerns led to proposals for ambitious new scientific programs to advance our understanding of the Earth system.

For these reasons, President Reagan in January of 1989 announced the United States Global Change Research Program (USGCRP) as a presidential initiative for fiscal year 1990 and the federal government's effort to establish the scientific basis for national and international assessments of changes, both natural and human induced, in the Earth system. President Bush reaffirmed the initiative, and congress codified the program through passage of the Global Change Research Act of 1990. President Clinton has continued to support the USGCRP as a priority in the national science and technology agenda. Parallel international programs already existed or were created dealing with the climate system, geosphere-biosphere issues, and interactions between the environment and human activity.

The USGCRP has grown programmatically from diverse roots in existing programs and planned activities within several federal agencies and reflects the evolution of closely related international programs such as the World Climate Research Program (WCRP), the International Geosphere-Biosphere Program (IGBP), and the Human Dimensions of Global Environmental Change Program (HDP).

In the early 1980s, the National Aeronautics and Space Administration (NASA) advanced a comprehensive new program: Mission to Planet Earth (MTPE). The centerpiece of the new program was an ambitious series of new satellites called the Earth Observing System (EOS). The satellite and the research and analysis programs of NASA's MTPE are key contributions to the USGCRP. Similarly, the early 1980s saw the emergence of the National Science Foundation's Global Geosciences initiative, and in 1989 the National Oceanic and Atmospheric Administration (NOAA) also began a Climate and Global Change Program focusing on related scientific objectives. With the formal initiation of the USGCRP as a presidential initiative in fiscal year 1990, contributions from the Department of Interior's U.S. Geological Survey were incorporated into the program.

Today, the USGCRP reflects the programmatic contributions of 11 federal agencies. Under the auspices of the National Science and Technology Council, the Subcommittee on Global Change Research of the Committee on Environment and Natural Resources provides the principal federal mechanism for integrating these individual agency efforts into a coordinated program. From the perspective of the participating agencies, the USGCRP fulfills three related objectives:

1. advancing scientific understanding of the global environment;
2. meeting agency-specific missions and responsibilities; and
3. providing reliable scientific information to support national and international decision making.

In the decade since the planning for the USGCRP began, much has been learned regarding the forces producing global change and the complexity of the connections between those forces and responses in the Earth system. We can point to many achievements, some scientific and some having significant economic value. A great deal of extremely high-quality science that is recognized worldwide for its excellence and leadership has resulted from the USGCRP. We have gained a greater appreciation of the need to link physical and natural scientific studies with those addressing the social sciences and economics. Thus, although the motivation for the USGCRP retains its original force and the scientific foundations remain strong, our experience suggests the need for improved management and broader participation and perspectives.

GUIDING PRINCIPLES

As the foundation for the recommendations that follow in this report, the Committee on Global Change Research:

- **confirms** that there have been many landmark scientific achievements of the U.S. Global Change Research Program;

- **reaffirms** that assessing the state of the Earth's environment and developing an understanding sufficient to predict how the planet's environment may evolve, including changes in the Earth's climate system, are important, tractable, and challenging scientific goals; and
- **urges** the aggressive pursuit of these goals.

Building on this foundation, the Committee on Global Change Research has enunciated the following set of **fundamental guiding principles** that should guide the development and implementation of the U.S. 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.
- In addition to observational systems implemented as explicit components of the USGCRP, the program should make use of **existing observational systems and data products** implemented in support of related environmental monitoring and Earth science programs (e.g., the ground-based and satellite observations which support operational weather forecasting).
- The USGCRP must utilize **advancing technology** in addressing these evolving priorities.
- An **open and accessible program** will encourage broad participation by the government, academic, and private sectors.
- Success in attacking 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.
- Successful implementation of the USGCRP and realization of its benefits require **informed leadership and collaboration** among the government, academic, and private sectors.

SCIENTIFIC DIRECTIONS

The activities of the U.S. Global Change Research Program are aimed at well-focused scientific issues of global change. These issues reflect the continuing evolution of global change research toward increasing levels of intellectual and programmatic integration and represent the appropriate principal foci for the USGCRP. The questions identified within each of these four scientific areas are intended to illustrate the lines of scientific inquiry that characterize the program's efforts. In the areas of seasonal to interannual climate and atmospheric chemistry, these questions reflect a highly refined set of specific priorities characteristic of the level of scientific and programmatic maturity achieved by USGCRP programs in those areas. The more general questions associated with climate change on the time scale of decades and with large-scale ecosystem change are characteristic of the somewhat more exploratory nature of research in these fields.

Seasonal to Interannual Climate Fluctuations

How does the El Niño/Southern Oscillation (ENSO) cycle in the tropical Pacific contribute to climate anomalies and related extreme events such as droughts, floods, and severe storms, and what other processes are involved? What are the controlling processes relevant to climate on seasonal to interannual time scales and regional to global spatial scales? Can we develop predictive models that include these processes? How can we predict seasonal to interannual climate fluctuations and associated extreme events, and how do we simulate the potential economic impacts on agricultural, water resource, and other socioeconomic systems?

Changes in the Chemistry of the Atmosphere

What are the trends and patterns of change in ozone concentrations in the stratosphere and upper troposphere, and the related trends and patterns of ultraviolet radiation at the Earth's surface and climate perturbations? What are the trends of tropospheric ozone, aerosols, and pollutants in the lower atmosphere? Can we model the physical and chemical processes in the atmosphere to permit prediction of changes in ozone, aerosols, pollutants, and related climate effects? Can we assess the implications of changing concentrations of ozone and other chemical species on human health and natural ecosystems?

Changes in Terrestrial and Marine Ecosystems

What are the trends and the geographic and temporal patterns of change in global land cover? What are the processes, both natural and human induced, that lead to changes in land cover, land use, and marine productivity, including such processes as deforestation, desertification, and loss of global resources, including biological diversity and productivity? How do managed and natural ecosystems interact with the atmosphere in the exchange of energy, water, carbon dioxide (CO₂) and trace gases, and how do those exchanges affect global and regional climates and water resources? What are the processes that control the exchange of biogenic trace gases between terrestrial ecosystems and the atmosphere? What is the distribution of sources and sinks for CO₂ and how is it changing? What processes govern the ocean's uptake of atmospheric carbon dioxide? What governs the variability of phytoplankton communities that form the base of the oceanic food chain? What are the links with higher species--fish, invertebrates, and mammals?

Changes in Climate over the Next Few Decades

What are the trends and patterns of change in the Earth's climate system, including the atmosphere, oceans, glaciers, sea ice, and the biosphere? How have these patterns varied in the past? What is the nature of the processes relevant to the dynamics of climate, including both internal factors such as water vapor, clouds, and heat transfer by the atmosphere and oceans, and external factors such as solar variability and volcanic activity? Can we develop predictive models of regional to global climate change over time scales from a decade to a century? What is the vulnerability of Earth systems, including economies, human health, and ecological systems, to climate fluctuations and changes on these time scales?

PROGRAM MANAGEMENT

The experience of the past decade or so has provided valuable insights into the management of large-scale Earth science projects. Those elements of the USGCRP that have worked well (e.g., the WCRP Tropical Ocean-Global Atmosphere (TOGA) Program and research on stratospheric ozone) have been focused on clearly defined Earth system problems and have been characterized by close collaboration within and among the national and international scientific communities and federal funding agencies on both development and the implementation. When this collaborative approach works well, the scientific community and the responsible parties in the federal government (both executive and legislative branches) share a scientific vision and a commitment to the programmatic discipline necessary to implement that vision:

- Scientific plans are developed with broad community participation.
- Federal funding agencies commit to a resource allocation strategy that adheres to those plans.
- Individual agency capabilities and assets are brought to bear on the problem, and program implementation decisions are made on the basis of scientific merit and relevance and are independent of agency boundaries.
- Responsibility for program direction and balance is shared among leaders in both government and the scientific community.
- National programs reflect clear ties to the related activities of our international partners and constitute formal U.S. contributions to established international global change research programs such as the WCRP, IGBP, and the HDP.
- Clear procedures for scientific review and guidance are established.
- Program participants in and out of government share responsibility for ensuring that research results are made available both to their scientific colleagues and to potential users.

The specific findings and recommendations that follow provide guidance toward taking the next steps in the evolution of the USGCRP and NASA's MTPE/EOS program.

Findings and Recommendations

PROGRAM-WIDE FINDINGS AND RECOMMENDATIONS

The past decade of research within the U.S. Global Change Research Program (USGCRP) has produced remarkable improvements in our understanding of Earth system behavior and its interaction with human activities. We have gained valuable insights into the characteristics of a successful global change research program. These insights lead the Committee on Global Change Research to the following programmatic recommendations for the USGCRP.

Recommendations

The USGCRP must

- maintain a **balanced** program of space- and ground-based observations, laboratory- and field-based process research, information management, modeling, prediction, and assessment activities in which the interaction among these program elements is as important as the success of each;
- identify clearly the **essential** elements of the program, while recognizing the contributions of related programs and activities;
- ensure the development and successful implementation of **integrated** scientific plans across agency boundaries;
- maintain strong and effective linkages with **international** global change research and observation programs; and
- obtain timely **guidance** from the scientific community on priorities, program balance, and direction.

The USGCRP is making an effort in each of these dimensions; however, the committee is concerned that the current efforts and their effectiveness may not be adequate to the task.

The USGCRP must encompass numerous scientific disciplines and areas of activity. Critical aspects of the program cross both discipline and agency boundaries. Thus, interdisciplinary and interagency linkages are central to successful implementation of the program. The needed **programmatic integration** is not currently being achieved adequately. Specifically, important elements of the USGCRP may be lost due to agency boundaries and individual agency funding difficulties.

- The USGCRP should be implemented as an **integrated program** of observations, process research, modeling, prediction, information management, and assessment that incorporates the unique assets and capabilities of the participating agencies and their extramural research programs. The necessary program integration and coordination must be achieved through **enhanced collaboration and cooperation among** the scientific community, the Congress, federal agencies, and the Executive Office of the President in the program's planning, implementation, and funding.

To that end,

- The **scientific community**, through its established advisory mechanisms, should
 - provide more timely **scientific guidance** on program priorities, balance and direction;
 - ensure **broader and more balanced** expert representation in advisory processes;
 - promote more effectively U.S. contributions to **international** global change research programs; and
 - conduct periodic **external reviews** to assess scientific progress and evaluate programmatic integration and performance.
- The **Congress** should
 - ensure that program authorizations and resource allocations to individual agencies are consistent with the implementation of an **integrated** program. (This is not currently being done); and
 - provide a mechanism for **bipartisan, bicameral oversight** of the effectiveness of the program in meeting the information needs of the nation.

- The Executive Office of the President and federal agencies should
 - implement USGCRP projects on an interagency basis using joint program announcements and pooled resources;
 - establish multiagency programs to integrate and jointly manage the crosscutting elements of the program such as training and education; and
 - provide a structure for effective interagency decisions on programmatic content and resource allocation including, where appropriate, designation of a lead agency or an interagency program office. The current approach to interagency coordination is not adequate, and its shortcomings are particularly damaging in these difficult budgetary times. The committee believes that the current interagency coordination structure lacks the level of programmatic discipline and agency accountability required to implement the USGCRP as a fully integrated interagency program.

The scientific problems of global change are complex and often cross the boundaries between traditional scientific disciplines. Young scientists, whose training is still relatively narrow, may thus have difficulty obtaining support, and their contributions may consequently be limited. The multidisciplinary character of the research, coupled with the disciplinary structure of traditional funding mechanisms, may hinder the emergence and recognition of capable leaders in science and government.

- The USGCRP and its component programs should encourage the recruiting and support of young scientists, particularly those capable of addressing inherently interdisciplinary Earth science problems.
- Professional societies, universities, and funding agencies should take new steps to ensure that scientists and program managers are recognized for unique contributions to the development and implementation of global change research.

SCIENTIFIC DOMAINS

The Committee on Global Change Research believes that four areas of Earth system science currently addressed by the USGCRP have reached a level of maturity at which enhanced, focused efforts promise tangible near-term benefits to society, including providing a sound, scientifically based assessment of the current state of the Earth's environment, while strengthening the scientific base for prediction of future global environmental conditions:

Seasonal to Interannual Climate Prediction

The concept of "end-to-end prediction" (i.e., the use of fundamental science to develop sound predictive schemes that yield products explicitly useful to human activities) motivates and guides all the components of this part of the program and sets its priorities and balance of elements, which include the following:

- development of coupled atmosphere-ocean-land models;
- combination of both in situ and satellite observations to initialize the models and an efficient data system to support this combination;
- investigation of poorly understood processes such as land-atmosphere interactions and atmosphere-ocean-land interactions outside the tropics; and
- research to support the application and evaluation of these forecasts.

Recommendations

- Direct research toward
 - improving the skill of **predictions of El Niño** for use in the tropical Pacific; and
 - **enhancing predictive skills in areas beyond the tropics** to the extent possible for future applications in sectors such as agriculture and water resource management.
- Enhance understanding of **land-atmosphere interactions** with
 - **an initial emphasis on the Mississippi basin**, to determine the predictability of regional precipitation and hydrologic water budget with future applications for agriculture and local economies; and
 - **a second focus on the Amazon basin** to further our understanding of energy and water exchange over the tropical land masses.
- Establish an **international research prototype prediction capability**, including a focused facility (the proposed International Research Institute) and a supporting research program in order to
 - accelerate the application of demonstrated predictive capabilities;

- secure multinational support for global-scale observing systems and international research programs; and
- focus research to extend predictive capabilities and applications.

Atmospheric Chemistry

The chemical composition of the atmosphere has been changing rapidly over the last several decades. Global change research has been successful in developing a scientific understanding of several of these changes such as stratospheric ozone depletion. However, the assessment and understanding of other problems such as tropospheric ozone and aerosols and their roles in climate and chemical processes remain largely inadequate.

Recommendations

- Enhance USGCRP research and its relationship to assessment in **tropospheric chemistry**.
- Improve estimates of **regional and national trends** in anthropogenic trace gas emissions.
- Enhance the focus on **tropospheric ozone** and its precursors through an **optimized combination** of space-based and in situ observations, laboratory studies, and modeling.
- Characterize the global distribution and processes associated with tropospheric aerosols.
- Extend to continental regions the current coastal and island networks monitoring biogenic gases.
- Conduct uninterrupted, careful monitoring and scientific assessment of **total ozone and other ozone trends in the lower stratosphere**, and evaluate their links to climate change.

Ecosystems

Prediction of future global environmental changes requires a scientific assessment of the current condition of terrestrial and marine ecosystems and an understanding of large-scale

terrestrial and marine ecological processes. Integrative Earth system models are important tools for assimilating and ordering this ecological information.

Recommendations

- Extend, both spatially and temporally, observing programs and process studies to **document changes** of the global **carbon cycle** in the atmosphere, in the ocean, and in the terrestrial system.
- Implement promptly national and international plans for scientific investigations of large-scale trends, patterns, and relationships among **vegetation, climate, and human land use** to document the interaction between natural and human systems for communication to resource managers.
- Study the **interactions between both managed and natural ecosystems and the atmosphere** in the exchange of energy, water, carbon dioxide, and trace gases and the effects of these exchanges on global and regional climates and water resources.
- Develop and validate **ecosystem components and surface-atmosphere** processes in integrative climate models.

Decadal to Centennial Climate

Anthropogenic forcing of climate change is an important problem, and significant additional scientific progress can be achieved that will serve society well. The problem should be studied in the context of natural climate variability over time scales of decades, centuries, and even millennia, and the interrelated trends in economies, technology, and demography.

Recommendations

- Investigate and assess changes in all the major **forcing factors** that influence climate variability and change and their interactions.
- Through models that **couple the components** of the Earth system--including the ocean, atmosphere, land, and ice--explore the major feedback processes, and thereby reduce the uncertainties in projecting future climate and its impact on human societies.
- Document the primary characteristics of the climate system by means of consistent **long-term observations**.

- Investigate critical economic, technological, and demographic trends that are affecting the ability of natural and human systems to cope with climate variability and change, including changes in urban infrastructure, farming technologies, trade, and water use and efficiency that can increase vulnerability or resilience to global change.

CROSSCUTTING ISSUES

The Committee on Global Change Research believes that a number of issues regarding the programmatic framework and supporting infrastructure for the USGCRP deserve special attention.

USGCRP Observational Strategy

The USGCRP requires an **integrated observational strategy** in which the choice of tools and approaches is driven by scientific needs and reflects an appropriate balance between in situ and remotely sensed observations to produce integrated information products for use by the research community and decisionmakers in the public and private sectors.

Recommendations

- The USGCRP should develop and implement a new **integrated observational strategy** that
 - identifies the **key scientific questions** to be addressed, characterizes the required measurements, devises the most appropriate, cost-effective observational system to secure them, and maintains the programmatic discipline required to ensure balance within that system;
 - in close collaboration with the scientific community, identifies the needs for **long-term observing systems** and addresses the many difficult problems involved in their maintenance and the archiving of their data, utilizing scientific symposia and publication in the open literature as essential elements in this complex task; and
 - takes advantage of advances in technology such as **unmanned aircraft and small satellite systems**, where appropriate, to support observational and process research needs.

NASA's Earth Observing System

The National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) should reflect the integrated observational strategy called for above. A series of previous reviews reshaped the program and guided it toward more responsiveness to scientific needs, greater resiliency, and increased opportunities for the introduction of new technology. In the plans presented to the present review, smaller spacecraft were scheduled to follow the AM-1, PM-1, and Chemistry-1 (Chem-1) missions. Furthermore, there was a shift by NASA in 1994 and 1995 from a fixed series of 9 missions involving intermediate-class spacecraft to a mixed fleet of 21 missions exploiting small to medium-class spacecraft. Our review supports that trend.

The present review also has confirmed that continued evolution is essential for successful implementation of NASA's Earth Observing System; therefore, the capability for future evolution must be maintained. In keeping with the above recommendation that the USGCRP develop an integrated observational strategy, and in anticipation of the advancement in understanding that will be achieved during this first phase of the EOS program, NASA, in concert with the USGCRP community, should consider carefully the observational strategy appropriate for the post-2004 era. Specific consideration must be given to the balance between monitoring, which requires certain long-term, calibrated measurements, and focused process studies, which may be accomplished in shorter periods. NASA's plans for biennial assessments are consistent with this recommendation and should also help ensure that the near-term observational strategy remains technologically current and scientifically relevant.

The present review has concluded, however, that structural changes to the near-term EOS missions beyond the limits achieved in the 1995 reshaping exercise would cause severe program dislocations. Further budgetary reductions or imposed constraints on technical options could mean the elimination of key sensors, slips in schedule, loss of data continuity, and the elimination of advanced technology development that could enhance future research and lower costs. Our review has concluded that a shift to smaller platforms for the first group of instruments would be premature, since it could eliminate key measurements.

As a result of technological advances, new scientific insights, programmatic changes by NASA in 1994 and 1995, and the evolving needs of the USGCRP as a whole, it is now appropriate to rebalance the program across space assets, in situ measurements, modeling and process studies, and the data and information management system. This rebalancing must be done carefully and must fully recognize the importance of certain calibrated long-term measurements for the USGCRP. The basis for this rebalanced EOS observational strategy is the 1995 reshaping of NASA's Earth Observing System.

Recommendations

- The USGCRP as a whole, and NASA's Mission to Planet Earth (MTPE) Program specifically, should maintain a **science-driven** approach to observation and information

technology that employs current technology while investing in the development of new technology with clear applications to support the program's specific scientific priorities.

- NASA should implement most of the **near-term components** of MTPE/EOS, including Landsat 7, AM-1, PM-1, and the Tropical Rainfall Measuring Mission (TRMM), **without delay** or reduction in overall observing capability.
- In situ observational programs, process studies, and large-scale modeling activities should be expanded (e.g., through **coordinated field programs** focused on high-priority scientific issues and utilization of advances in technology).
- NASA should develop **advanced technologies to reduce the costs of continuing the essential observations** initiated by the AM-1, PM-1, and Chem-1 missions.
- Because global mapping of tropospheric ozone is central for understanding and monitoring changes in the chemistry of the troposphere, the tropospheric component of the Chemistry-1 mission should be focused on **global measurements of tropospheric ozone** and its precursors in conjunction with the international ozone network.
- NASA should evaluate the capabilities of both space-based and in situ approaches to define the best scientific framework for obtaining critical information on ozone precursors in order to interpret tropospheric ozone trends. This evaluation must involve a wide spectrum of the scientific community. In addition, the evaluation should consider the critical aspects of the coupling between the chemistry of the troposphere and the stratosphere and the contributions from the European ENVISAT mission. An overall need to simplify and focus the Chem-1 mission and thereby reduce its cost and complexity must be recognized; however, **the Chemistry-1 mission should not be delayed.**

Coordination with Other Space Remote-Sensing Programs

Convergence of observing activities among the programs of U.S. agencies and those of other nations offers the potential for significant savings. However, the current convergence planning process does not have the charter or authority to consider the scientific requirements of USGCRP.

Recommendations

- Science requirements should be considered for inclusion in the specifications for the converged NOAA/Defense Meteorological Satellite Program system.
- In 1996, a **scientific and technical review of the federal convergence activities** should be conducted with special attention to their connection to the USGCRP.

Small-Satellite and Advanced Technologies

Those small satellites that have relatively low costs and short development times may provide mission and programmatic flexibility that can stimulate innovation. They can also provide a means to introduce new technology and conduct focused observing missions. The reshaped 1995 MTPE/EOS program anticipates the application of such satellites where appropriate. In some cases, physics, economics, and engineering constraints may preclude the application of small satellites. A balanced architecture for MTPE employs satellites of various sizes as appropriate to scientific needs.

Recommendations

- NASA should explore the possibility of using **advanced technologies** on small satellites for measuring tropospheric aerosols and winds, soil moisture, and other key parameters through laser, radar, and other advanced technologies.
- The Earth sciences component of the New Millennium Program (NMP) should be **integrated** into the Mission to Planet Earth Program; it should be science driven and not treated as a separate technology program.
- A small-satellite program should recognize two **linked challenges**:
 1. to develop capabilities that will **lower mission costs**; and
 2. to develop measurement capabilities that **advance our observational capabilities** in critical priority areas in Earth system science and global change.

Again, however, any shift in observational strategy and its implementation must be done carefully and must fully recognize the importance of certain calibrated long-term measurements for the USGCRP.

Practical Applications of EOS

MTPE/EOS, including the TRMM, Landsat 7, AM-1, PM-1, Chem-1, and the associated smaller missions, represents significant advances over previous space observation systems. The capabilities of these systems will contribute to practical applications such as natural hazards mitigation, water resources management, and food and fiber production, as well as advances in the Earth sciences.

Recommendation

- The capabilities of MTPE/EOS should be exploited fully via enhanced public access to the information products.

EOS Data and Information System

The EOS Data and Information System (EOSDIS) is an essential component of the EOS program for linking space and ground observations and converting them into accessible geophysical information that will contribute to new scientific understanding. Originally designed by NASA as a centrally controlled and operated system to meet ambitious performance and reliability requirements, the system was redesigned after a National Research Council (NRC) review as a logically distributed system based on a client-server model in order to accommodate evolving computer system concepts and technologies.

Despite this improvement, current performance requirements, a centrally controlled system of stand-alone computer centers, and an extensive engineering and management superstructure are stressing the bounds of affordability. Moreover, the committee is concerned that the management structure may not be sufficiently flexible to meet rapidly evolving scientific needs and opportunities. The current system should therefore be reconsidered in light of technological opportunities and possible management efficiencies.

The present problems with EOSDIS are not related to engineering concepts. Instead, the concerns are much more fundamental and are related directly to the conceptual model of its operations and management. For EOSDIS to succeed in enabling new levels of achievement in the Earth sciences and applications in a wide range of activities in the public and private sectors, its management must be open and community based. That is, the community of researchers and users must take the lead in making key decisions, and the assignment of responsibilities and evaluations of performance must be based on peer review. The system must encourage innovation and creativity through broad participation of the scientific, public, and private sectors.

Recent progress in redesigning the EOSDIS architecture, coupled with extraordinary new capabilities in computer telecommunications and recent experience by the scientific community in the management of large and diverse data sets, now permits a **significant change in the**

conceptual model that governs the management and operation of the system. Thus, although the initial processing (e.g., through geo-located and calibrated radiances at the spacecraft) of the data flowing from spacecraft should remain with NASA and could be conducted largely at existing centers, the subsequent processing and creation of products useful in science and applications should be distributed widely and thereby take advantage of the concepts and technology involved in the rapid growth of the Internet and the World Wide Web.

Thus, the current distributed client-server design of EOSDIS is responsive to community needs, and its engineering development, and should continue. However, the Committee on Global Change Research believes that the **EOSDIS management and operations concept** should be redefined to involve the broad user community effectively.

Recommendations

- The components of the EOSDIS now under development for flight control, data downlink, and initial processing should be retained but **streamlined**.
- Responsibility for product generation, publication, and user services should be transferred to a **federation** of partners selected through a **competitive** process open to all.

Representative actions to respond to these recommendations are given in Appendix F with the aim of aiding NASA, the EOS investigators, and EOSDIS contractors in designing and conducting a collaborative study of the feasibility and cost of the proposed approach.

Clearly these recommendations imply a major change in EOSDIS management and operations. Under the proposed concept, the initial processing of observational data from EOS spacecraft would remain the responsibility of NASA. After a transition period, however, the responsibility for generating products and accounting for interdependencies among instruments would be distributed through a competitive process to a federation that might include government, academic, and private sector entities. Members of the federation would receive geophysically located, calibrated radiances over the Internet or via overnight express; process the data to higher levels, resolving any necessary interdependencies; create appropriate data products; and make them available to users over the Internet or by shipment of media. Among the higher-level data products that would be produced and distributed in this manner would be EOS Standard Data Products.

To be successful, this approach must incorporate community leadership and acceptance of responsibility in decisionmaking, and it must encourage innovation and creativity by providing users with ready access to scientifically meaningful data sets. The new approach must be based on powerful incentives, permissive standards that encourage wide participation and electronic publication of results, and meaningful criteria for assessing the performance of the partners

responsible for data products and user assistance. In implementing this recommendation, there must be a clear recognition of the overriding importance of long-term maintenance and availability of the data, including the original Level-0 data, the geophysically located and calibrated radiances, and the higher-level products.

This intellectually inclusive approach will stimulate scientific creativity and innovation while providing increased return on the national investment. Moreover, it will create a strong foundation for the broader Global Change Data and Information System. It will generate a new approach to the interactive management and use of distributed data sets that, with an appropriate set of standards and protocols, will provide a new capability for collaborative and innovative exploitation of complex arrays of data and information in a wide range of public and private endeavors.

CONCLUDING THOUGHTS

The U.S. Global Change Research Program (USGCRP) recognizes the intellectual evolution of Earth system science and the magnitude of the scientific challenge of understanding and predicting global change. The scientific foundations, motivations, and goals of the USGCRP remain valid guides for the conduct of the program. Nevertheless, because of scientific advances, emerging technologies, and new concepts of effective management, the program can be refined in significant ways to become scientifically stronger, to be balanced better, and to produce greater return on the national investment. The Committee on Global Change Research, assisted by the workshop participants, assessed the USGCRP and NASA's MTPE/EOS program in the context of these new scientific and management insights and identified a recommended path for the future of the USGCRP. The proposed rebalancing of the program would offer the potential for significant economies (e.g., by simplifying the Chem-1 mission, by streamlining the data downlink and initial processing of EOSDIS, and by employing a federation of partners in EOSDIS for product generation). To ensure scientific success, it is necessary to direct resources toward (1) expanding in situ observations, process studies, and large-scale modeling; and (2) developing advanced technology to reduce the costs of second- and third-generation missions and to open new scientific opportunities.

The Committee on Global Change Research believes that this rebalancing of resources is central to the recommendations in this report.

Appendixes

The following appendixes provide short summaries of the deliberations of the working groups on the four scientific areas of the U.S. Global Change Research Program (USGCRP) and on the role of the National Aeronautics and Space Administration (NASA), Mission to Planet Earth/Earth Observing System (MTPE/EOS) and EOS Data and Information System programs in the context of the overall program. These documents were written by the designated working group chairs and reflect their sense of the views of working group participants, further illuminated by extensive plenary discussions in the course of the workshop. These documents provide a window into the information, analysis, and discussion drawn on by the committee in formulating its conclusions and are presented here to provide a background for the preceding report. However, they do not represent approved conclusions or recommendations of the workshop or of the responsible committee. The chairs of the six working groups are also preparing a set of more complete interim working documents that describe their deliberations in more detail and will be used as critical input to the second phase of the comprehensive review of the USGCRP.

A

END-TO-END SEASONAL TO INTERANNUAL PREDICTION

Working Group Participation

Edward S. Sarachik, *Chairman*

Otis B. Brown

Moustafa T. Chahine

William E. Easterling

Roger B. Lukas

Piers J. Sellers

James Shuttleworth

Soroosh Sorooshian

Peter J. Webster

Designated Federal Liaison: J. Michael Hall

Rapporteur: Frank Eden

WORKING GROUP SUMMARY

Edward S. Sarachik, *Chairman*

In terms of climate prediction, the last ten years have witnessed a revolution in our ability to observe, understand, and predict a year in advance the fundamental dynamics of the El Niño/Southern Oscillation system. Success to date suggests that further research and development could lead to climate predictions that can provide advanced information to reduce the impacts of such destructive natural climate fluctuations as droughts, which lead to forest fires and crop failures; floods, which lead to loss of life and stoppage of river commerce; and heat and cold waves, which lead to human misery and deprivation.

We make a prediction every time we expect this year's summer to be basically the same as last year's. It is this expectation of the regular return of the seasons that is confounded when unusual spells of weather cost us time and money because our expectations turn out to be false. The need to predict, when possible, the *actual* state of the climate, months to a year or so in advance, motivates programs on seasonal to interannual prediction. What we now have the ability to accomplish motivates a great deal of scientific observation, research and modeling. The science is fundamental, yet the payoffs are short term and tangible.

Progress by a determined community of government and university meteorologists, oceanographers, and hydrologists with multiagency support (led by National Oceanic and Atmospheric Administration (NOAA) Office of Global Programs) has been rapid and remarkably successful: We already have begun to predict aspects of El Niño in the tropical Pacific, and these forecasts have benefited countries affected by El Niño (Peru, Brazil, Australia, Chile, and Columbia, the Philippines, and the U.S. Pacific Islands). Progress over the next few years will determine whether this predictive capability can be developed fully for use within the United States.

In the early days of climate research, science was the province of a few agencies, often with diverse objectives. The U.S. Global Change Research Program (USGCRP), aided by the Office of Management and Budget (OMB), allowed the agencies to focus their resources and to function in a coordinated way with advice provided by the National Research Council (NRC). As a result of these programs on seasonal to interannual variability, we have moved from a time in which the El Niño phenomenon could barely be observed, to a time in which data on the actual state of the surface and subsurface tropical Pacific to a depth of 500 meters, along with predictions based on these observations, are accessible to any researcher via desktop computers.

Science Questions

The creation and evolution of USGCRP programs on seasonal to interannual variability are based on four fundamental scientific questions:

1. *Where* is there significant seasonal to interannual variability in the Earth's climate system, and what are the patterns of this variability?

2. What *mechanisms* underlie this seasonal to interannual variability, and how do they differ across space and time?
3. What are the *effects* of seasonal to interannual variability, for example, on economic stability and competitiveness; on agriculture, natural resources, water resources and hydrology, trade routes and transportation, etc.; and on natural hazards such as floods, droughts, forest fires, heat waves, and consequent health effects?
4. How *predictable* are seasonal to interannual climate variations and their effects?

USGCRP RECORD IN UNDERSTANDING SEASONAL TO INTERANNUAL CLIMATE VARIATIONS

Through programs developed under the USGCRP (with the cooperation of OMB and support from Congress)--primarily TOGA (Tropical Oceans Global Atmosphere), its successor program CLIVAR/GOALS (Global Ocean Atmosphere Land System), and GEWEX (Global Energetics and Water Experiment)--we have *begun* to understand seasonal to interannual climate variations in limited regions of the Earth, especially the phenomenon referred to as El Niño. We can now see, understand, and predict (to a degree usable for some regions of the world) the climate variations that characterize El Niño. We have also begun to appreciate the role of land processes and hydrologic systems in seasonal to interannual climate variability or predictability.

Some remarkable achievements over the last ten years have pioneered short-range climate prediction and indicated a path to the eventual prediction of seasonal to interannual climate variations over the U.S. These include the following:

- development of a mechanistic understanding of the El Niño/Southern Oscillation and its influence on the climate system;
- development of coupled atmosphere-ocean models for the tropical Pacific capable of simulating the El Niño/Southern Oscillation (ENSO) phenomenon and its influence on the climate system;
- building, deployment, and maintenance of a basin-wide multinational observing system with data freely available in real time (see Figure A-1);
- planning, implementation, and analysis of a multinational study designed to quantitatively define the interaction of the atmosphere and the ocean in the western equatorial Pacific;
- development of usable forecasting skills for sea surface temperature variations and rainfall in the tropical Pacific;

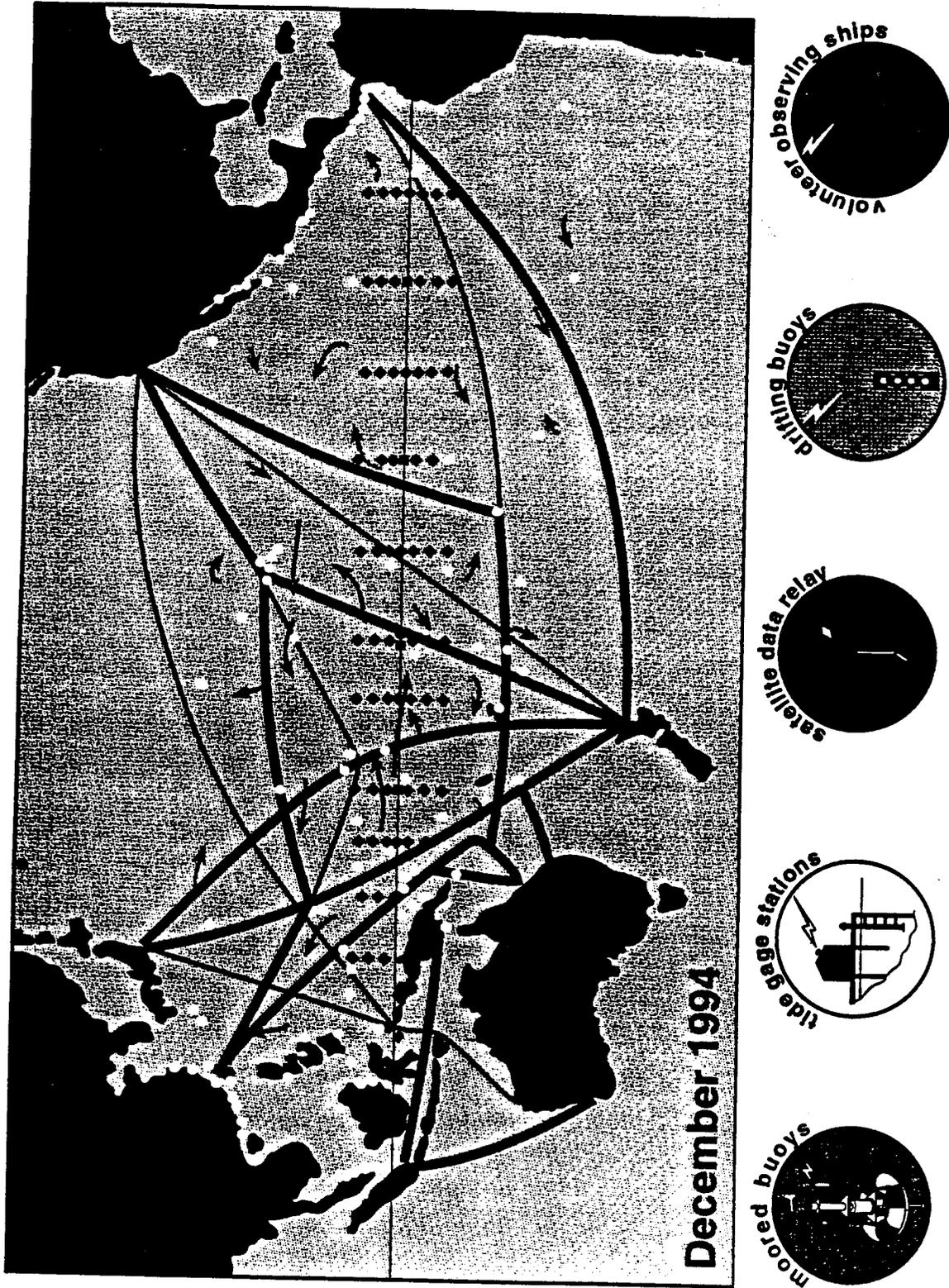


FIGURE A-1 Tropical Pacific Ocean Observing System

- design and partial implementation of an end-to-end prediction system that will bring together observations and models for us in regions affected by El Niño;
- the ability to extend forecasts to a month in advance for excess rainfall and floods in the Mississippi basin by use of high-resolution models;
- identification of the remote effects of ENSO and the local effects of land surface on the U.S. drought of 1988;
- planning of a multinational study to investigate rainfall patterns and variability and interactions with the land surface in the Mississippi basin;
- deployment of a major radiation-observing network in Oklahoma and Kansas to calibrate climate models and satellite measurements;
- initiation of activities to expand both the time range of and the spatial extent of prediction to greater areas of the globe including land processes;
- demonstration, principally by large-scale field experiments, of the importance of soil and vegetation processes in controlling land surface-atmosphere exchange of energy, water, and carbon, satellite data are now being used to define the continental patterns of these exchanges;
- initiation of ensemble forecasting to explore the effects of El Niño variability over the U.S., and extension of the predictability of seasonal to interannual variations over U.S. regions known to be affected by El Niño (see Figure A-2).
- demonstration of the benefits of El Niño forecasting to the countries and regions affected by it.

These accomplishments have arisen from focused U.S. contributions to international programs, including TOGA, GOALS, and GEWEX. However, a great deal of activity in USGCRP agencies on seasonal to interannual climate has not been part of these focused efforts and therefore has not been nearly as effective in advancing the highest priorities.

OPPORTUNITIES FOR USGCRP IN SEASONAL TO INTERANNUAL CLIMATE VARIABILITY AND PREDICTABILITY

Based on the results of the TOGA program, the research community believes that future opportunities for the USGCRP will best be achieved in the context of

- a demonstration research project for an end-to-end seasonal to interannual prediction capability, initially involving El Niño.

NORTHERN HEMISPHERE WINTER

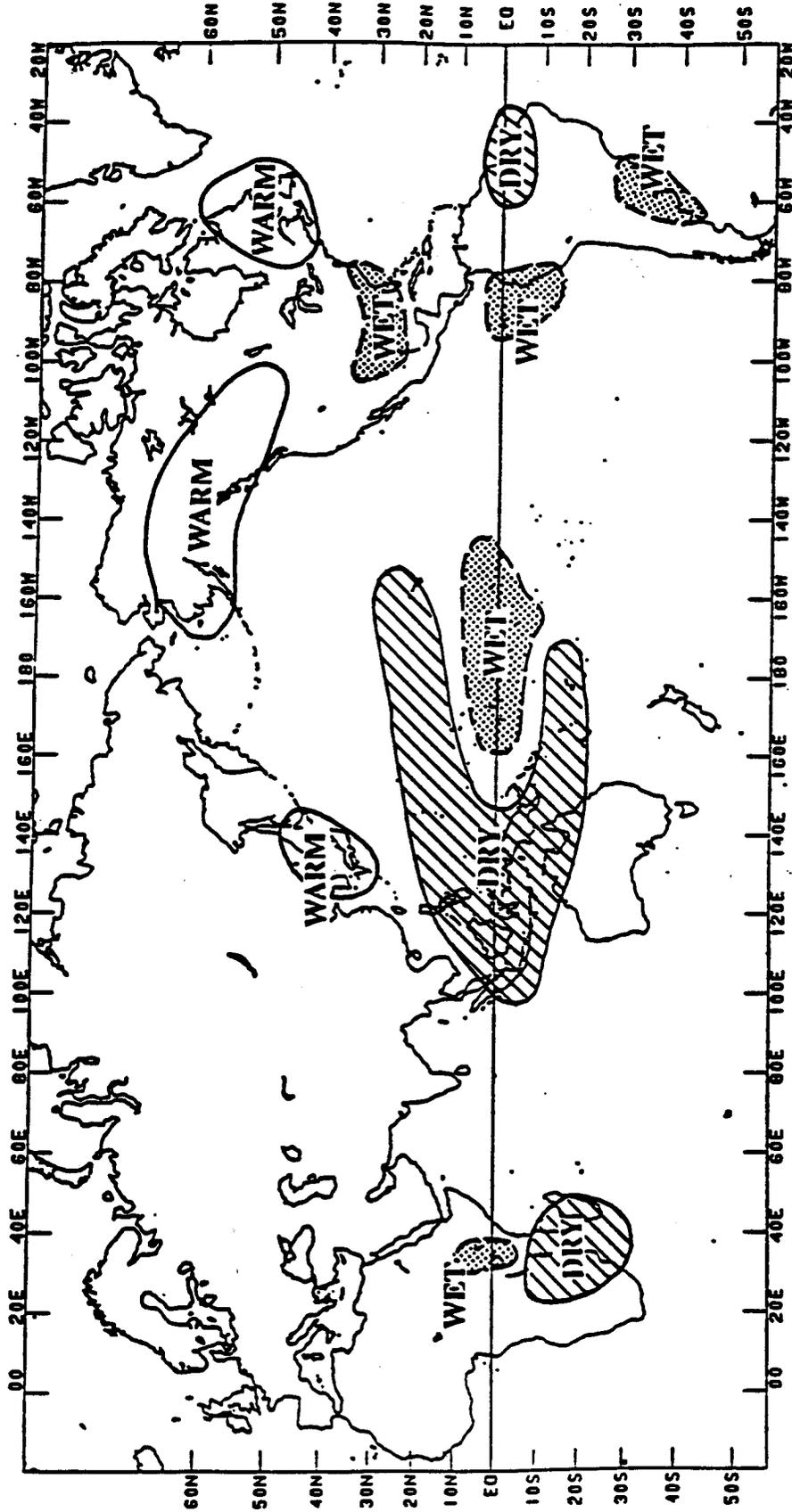


FIGURE A-2

Such a demonstration project is reflected in national and international global change program documents that describe the need for research programs, such as CLIVAR/ GOALS and GEWEX, and call for the establishment of an international research institute (IRI) for seasonal to interannual climate prediction. Planning documents for elements of the World Climate Research Program (WCRP) and the U.S. Seasonal to Interannual Climate Prediction Program (SCPP) point to the establishment of an IRI as an important mechanism to

1. accelerate the application of existing predictive skills;
2. ensure multinational support for a program of seasonal to interannual climate prediction, including critical support for the required observing system;
3. identify scientific priorities associated with extending predictive capabilities; and
4. guide the allocation of resources accordingly.

The broad outlines of such a demonstration project can be diagrammed as shown in Figure A-3.

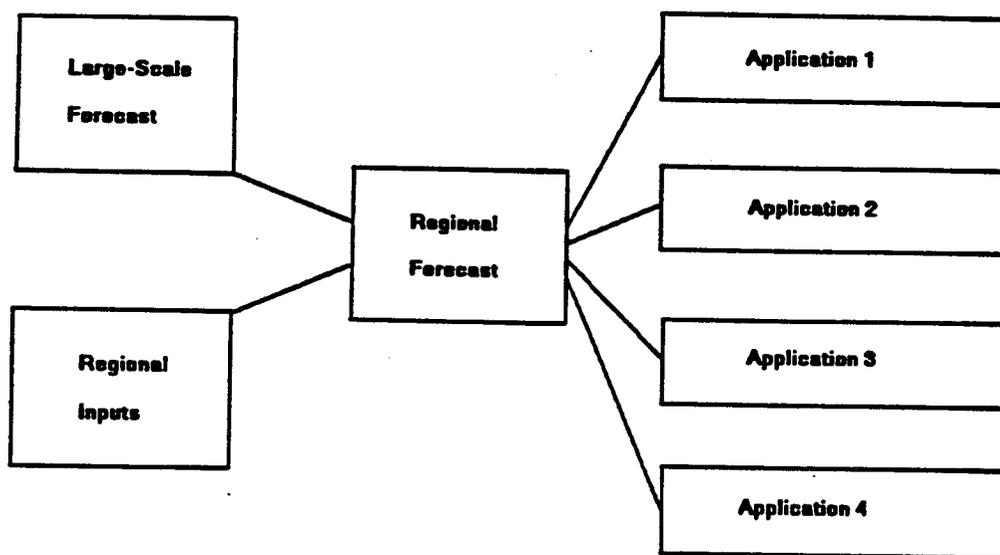


FIGURE A-3

Since all useful forecasts are local, a large-scale forecast is, by itself, not sufficient for practical application. Local data (models, statistical data, etc.) must be added to the large-scale forecast to produce a regional forecast. This regional forecast is then used for application to a sector. Different applications may require different types of local forecasts: for example, applications to fisheries may require, among other things, ocean temperature, whereas applications to agriculture and water resources will require, among other things, rainfall amounts.

In this context, an end-to-end prediction system can be defined as consisting of the following steps:

- **A model** must be developed to make the predictions.
- **Data** must be quality controlled and assimilated into a form the model can accept.
- **Initialization:** The data and the model must be combined to provide an optimal estimate of the state of the coupled system.
- **Large-scale prediction:** One, and perhaps an ensemble, of predictions must be made.
- **Evaluation:** The data must be used to determine the accuracy of the forecast and provide an objective measure of skills and uncertainties.
- **Assessment:** The impacts of seasonal to interannual variability and must be examined, an appropriate regional site and scale must be chosen.
- **Regionalization:** Regional data and models must be combined to provide data products for input to forecasts.
- **Regional forecasts:** Regional data products must be combined with the large-scale forecast to provide a regional forecast.
- **Applications:** Regional forecasts can be applied to different sectors.
- **Effectiveness of applications:** Appropriate ways must be developed to distribute and communicate information (including uncertainties) about seasonal to interannual variability, prediction, and applications to a broad user community.
- **Evaluation of applications:** The impact of the applications and the effectiveness of the actions taken must be evaluated.

Implementation

Implementation of the concept of end-to-end prediction requires a number of things that can be diagrammed as shown in Figure A-4.

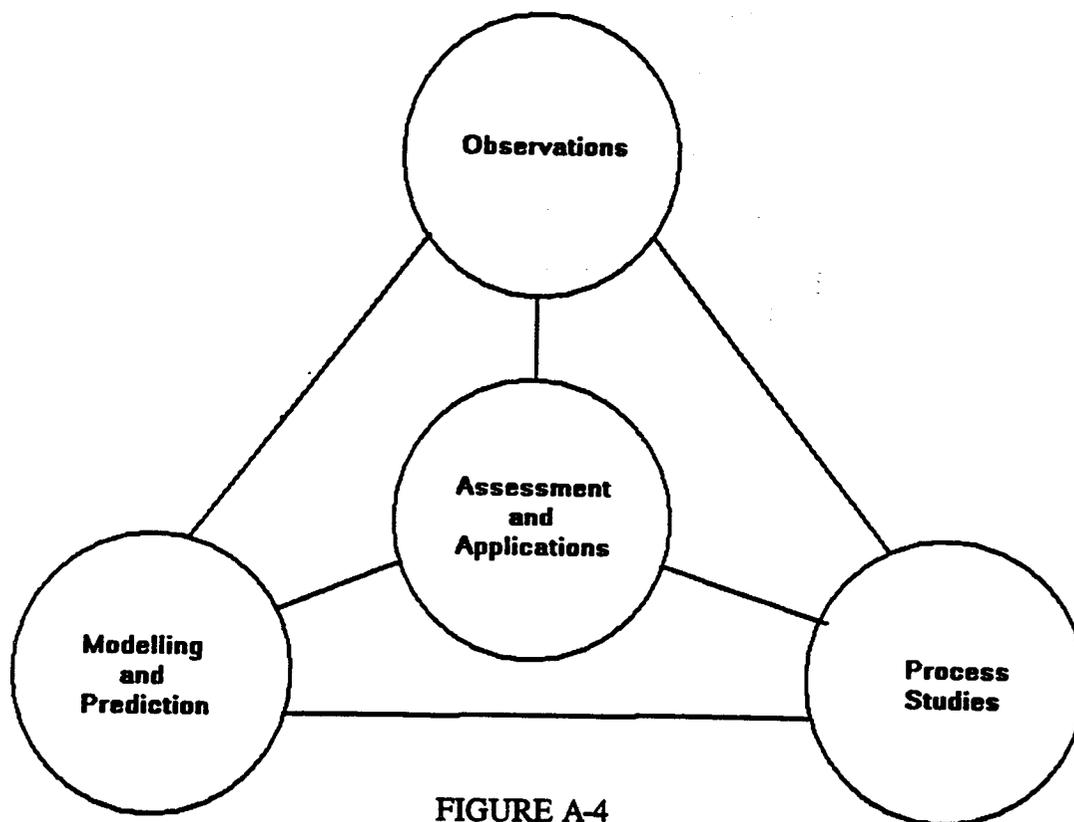


FIGURE A-4

The strong interaction and balance among all the elements in the figure are crucial. End-to-end seasonal to interannual prediction **requires** the development of coupled atmosphere-ocean-land models. It **requires** that observations be available and a procedure developed for initializing the forecasts. It means that remote and in situ observations must be combined for this initialization and that an efficient data system must be established for this combination. It **requires** a procedure for validating predictions. It **requires** that poorly understood or modeled processes be investigated and sets priorities for these processes. Since climate information, to be useful, must be brought down to the local level, it **requires** adding local information and making region-specific forecasts. Then, the sector of application and its normal mode of operation in the absence of additional information must be identified and understood. Finally, the information must be combined with the forecast and presented to the user in a way that guarantees maximum utility.

The basic implication of this concept is that it guides, in a focused way, what needs to be done; provides a measure of the value of an activity in terms of its role in the end-to-end system; indicates gaps or imbalances in the activities (what is not being done); provides useful results on both a short-term and an ongoing basis; and has a built-in means of evaluation: the skill of prediction and the success of the applications. Conversely, this end-to-end activity is integral: no part of it can be compromised without affecting the ultimate skill of the prediction and the usefulness of the applications.

The working group participants identified some priorities within individual components of this integrated program on seasonal to interannual climate prediction.

Models

Research is needed to enhance the understanding of a crucial, but poorly understood, aspect of climate models: (1) land-atmosphere interactions, with initial emphasis on land-atmosphere interactions over the Mississippi and the Amazon basins, and (2) the characteristics and predictability of precipitation in this region and other land regions that affect seasonal to interannual predictability (GEWEX).

Observing System

General Principle

A general observing system for end-to-end predictions must be some *combination* of in situ and remote observations and must lead to model-assimilated data.

The reasons for this principle are numerous: Remote systems generally require surface information continuously. This information is used for continuous calibration and to ameliorate gaps that always arise from remote observations. Conversely, in situ observations can never be global; they require remote measurements to achieve global coverage. Both types of observations must contribute to the initialization and validation of predictions and, therefore, to a model-assimilated data product.

We can identify the priorities for seasonal to interannual prediction:

- Atmosphere: upper air data as given by the World Weather Watch--precipitation, water vapor distributions and profiles, top-of-the-atmosphere radiation, cloud and aerosol properties and distributions in the vertical and horizontal;
- Ocean: *sea surface temperature, sea surface winds, upper ocean subsurface temperatures*, precipitation, sea level, salinity, sea ice
- Land: soil moisture, soil type, topography, vegetation, surface temperature, precipitation, snow cover, runoff, and fields of surface radiation coordinated with top-of-the-atmosphere radiation.

The quantities are not prioritized among atmosphere, land, and ocean, and only for the ocean are relative priorities identified (*italicized quantities represent the highest priorities*). Note that precipitation occurs in all three lists. Maintenance of the CLIVAR/GOALS observing system in the tropical Pacific and its appropriate expansion combining in situ and remote observations (including Mission to Planet Earth) over other oceans and over land are essential.

Process Studies

Process studies can be observational, theoretical, or computational and can range from pencil-and-paper calculations to large observational field programs. In order to apply to end-to-end prediction, they must focus on those inadequacies in the models, observations, or applications that affect the skill of prediction or the success of applications.

The skill in seasonal to interannual prediction within the U.S. is still insufficient to be used effectively but it is being developed in a planned, phased process. This process begins by further improving the skill of predicting of El Niño in the tropical Pacific; then expanding the regions of application around the tropics (including the monsoon regions of North America, especially Arizona, Texas, and New Mexico; South America; and Southeast Asia); next investigating predictability in midlatitude areas (including the U.S. West Coast and Southeast) that derive their predictability from the remote effects of El Niño; and finally, investigating whatever predictability may be further exploited from atmosphere-ocean-land interactions totally outside the tropics (CLIVAR/GOALS and GEWEX).

These process studies are best pursued via U.S. contributions to the high-priority international programs CLIVAR/GOALS and GEWEX, and via successful implementation of the U.S. SCPP, including establishment of an IRI.

EVALUATION OF USGCRP PROGRAM MANAGEMENT

Accomplishments thus far have resulted in a new paradigm in which the concept of end-to-end prediction motivates and guides all program components and determines the priorities and balance among program elements.

The concept of end-to-end prediction can also be used to focus and evaluate relevant research by imposing a discipline on the process and defining the priorities for a carefully balanced program. This balance is crucial: since all elements depend on each other, no element can be compromised without damaging the entire enterprise. It presents a method of R&D in which success can be demonstrated by the development of forecast skill and by the money and lives saved by applications of predictive information. The program requires careful coordination, good advice and oversight, and a stable and balanced funding profile, with focused contributions by the agencies involved in seasonal to interannual prediction. This country has an enthusiastic and able body of scientists eager to tackle the scientific problems involved in developing end-to-end prediction on these time scales. The return for investment now will pay off in the short run and eventually lead to a permanent prediction capability that will benefit the entire country.

In this context, the working group identified some program management principles that must apply in supporting and managing a demonstration research program on end-to-end seasonal to interannual prediction.

Success requires a management structure in USGCRP (with OMB, the Office of Science and Technology Policy (OSTP), and the Congress) that will

- ensure that the highest-priority programs are protected both within and between agencies;
- ensure that support is focused on the highest-priority programs and that balance is maintained among program components, and
- ensure that participating agencies contribute (or not withdraw) resources for the highest-priority programs.

The working group emphasized that these requirements are not currently being fully met.

OPPORTUNITIES FOR INTERACTION WITH OTHER ELEMENTS OF USGCRP

Seasonal to interannual climate variability interacts strongly with other elements of the USGCRP. Only a few examples are given here.

Decadal to Centennial Variability and Change

The attachment to this appendix provides some details on the connections between research on seasonal to interannual climate variability and investigations of decadal to centennial climate change. Examples include the following:

- El Niño has a predominantly interannual time scale but is also modulated on decadal time scales. This decadal modulation has teleconnection to higher latitudes and has been shown to be responsible for the greater warming over land and cooling over ocean during the winter than during the summer. Therefore, El Niño processes are an important source of decadal climate variability.
- The subtropics of the Atlantic have a dipole in sea surface temperature that helps determines the location of rainfall in both northeastern Brazil and the Sahel. The variability of this dipole is both interannual and decadal and therefore is a natural contact point between the two scientific areas.

Atmospheric Chemistry

Since cumulus convection in the tropical Pacific has the time dependence of El Niño, and since it both directly transports water vapor (and other trace gases) into the stratosphere and affects the height of the tropopause, there will be a modulation of stratospheric-tropospheric exchange.

- Tropospheric temperature, especially in the tropics, varies with El Niño and, through temperature and water vapor, affects all aspects of tropospheric chemistry.
- Under normal conditions, the tropical Pacific is a net source of carbon dioxide and contributes 1 gigaton per year to the atmosphere. During warm El Niño conditions, this flux of carbon dioxide is severely reduced or completely eliminated. El Niño modulations of carbon dioxide are therefore important components of the natural carbon budget of the atmosphere.

Large-Scale Ecology

- All growing systems near the surface respond to sunlight and water at the surface. Interannual modulations of both water and sunlight affect the characteristics and response of these ecological systems.
- Extreme conditions during El Niño (e.g., rainfall in the normally arid Peruvian coastal plains) can stress ecosystems used to more subtle variations.

MISSION TO PLANET EARTH/EARTH OBSERVING SYSTEM (MTPE/EOS) AND SEASONAL TO INTERANNUAL PREDICTION

1. GOALS, GEWEX, and SCPP look to MTPE to help provide the capability to expand prediction skill around the globe and to higher latitudes (including land), and to better assess the impacts of seasonal to interannual variability. It can do this by
 - measuring the high-priority quantities subject to the principle that all USGCRP observations are combinations of in situ and remote measurements leading to model-assimilated data products when possible and desirable,
 - guaranteeing the continuity and quality of measurements by overlapping in situ and remote measurements, overlapping remote measurements, and continuing in situ validation of remote measurements, and
 - supporting and enhancing the core programs GOALS, GEWEX, and SCPP, including the IRI.
2. The Earth Observing System/Data Information System (EOSDIS) should provide *products* that
 - contribute to data assimilation for initialization of end-to-end seasonal to interannual predictions;

- are useful and easily accessible for assessing the impacts and validating predictions of seasonal to interannual variability and the applications of such predictions; and
 - combine in situ and remote data as appropriate.
3. EOSDIS should include a *process* to characterize user needs and design useful products for them.

CONCLUSION

The U.S. public responds to what it reads and experiences and has come to expect predictions of heat waves, destructive hurricanes, excess rainfall leading to floods, and spells of drought. The skill for seasonal to interannual prediction within the United States at the moment is too low to be used effectively. However, it is being developed by a planned, carefully phased process that begins by concentrating on regions where predictability has been proven, particularly El Niño in the tropical Pacific. This process then concentrates on international programs such as CLIVAR/GOALS and GEWEX, and on implementation of the U.S. SCPP, including the IRI.

ATTACHMENT

**Intersection of Seasonal to Interannual and
Decadal to Centennial Climate Variability and Prediction****Roger B. Lukas**

The past few years have seen ENSO variations in the tropical Pacific unlike anything in the past 100 years. The probability of observing this type of variability by chance is 1 in 2,000 if the recent climate record is stationary with respect to S-I variability. Thus, the inescapable conclusion is that S-I variability is nonstationary, and it remains to determine whether this is a characteristic of natural variability on longer time scales or whether it is related to enhanced greenhouse warming.

Recent analysis showed that the amplitude and phase of the annual cycle in the SOI have varied substantially during the 1900s. It is well established that the existence and character of model ENSOs depend on the annual cycle that is either produced by the model or specified a priori. One might view ENSO as a perturbation of an unstable annual cycle.

A recently discovered global mode of the ocean-atmosphere-land system involving winter warming over northern land masses and winter cooling over northern oceans showed that surface temperature anomalies varied out of phase on short time scales, but they have been locked into a warm phase over land masses for at least the past two decades.

Together, these results suggest that decadal time-scale processes are interacting with ENSO. Further, it appears that these modulations are impacting the recent prediction skill for ENSO. Thus, it is very important for the seasonal to interannual climate component of CLIVAR and USGCRP to work in collaboration with the decadal to centennial climate component to understand the mechanism(s) responsible for these modulations of ENSO.

Some hypotheses can be advanced to explain these and related observations. Two involve tropical-extratropical linkages within the ocean, operating on much longer time scales than such linkages in the atmosphere. One hypothesis involves long oceanic Rossby waves generated along the eastern boundary of the Pacific during ENSO, and their subsequent propagation westward across the basin and interaction with the atmosphere through sea-surface temperature (SST) variations. Another hypothesis involves the interplay of the shallow thermohaline overturning cell in the North Pacific coupling the tropical and subtropical wind-driven gyres, with anomalous heat and freshwater flux forcings in the subtropical gyres (forced in part by ENSO) manifest later as equatorial thermocline anomalies.

A combination of monitoring, modeling, and process research is appropriate to pursue one or more of these hypotheses. Such an integrated approach to understanding the decadal modulations of ENSO provides motivation for continuing observations in a research context. Existing elements of the GOALS (former TOGA) observing system and the ongoing World Ocean Circulation Experiment (WOCE) program already provide a large-scale monitoring context for the upper Pacific Ocean. A sequence of process studies is proposed to address the processes that are critical to these (and other possible) hypotheses in order to ensure that they are properly captured in coupled models that can be used to rigorously test the motivating hypotheses. Such an approach has been used quite successfully during TOGA.

B

ATMOSPHERIC CHEMISTRY

Working Group Participation

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WORKING GROUP SUMMARY

Guy P. Brasseur, *Chairman*

Changes in the chemical composition of the atmosphere on the global scale are not hypothetical. They have been occurring rapidly over the last hundred years. Increases in carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and chlorofluorocarbons (CFCs), and decreases in stratospheric ozone are well documented. Volcanic dust has been observed to rise to the stratosphere and impact the global climate for periods of months to years. Surface ozone abundances in industrialized regions have changed dramatically as a result of surface input of NO_x and volatile organic carbon compounds (VOCs), but changes in midtropospheric ozone on the global scale are less certain. The release of anthropogenic nitrogen and sulfur compounds has led to an increase in the acidity of precipitation and has increased the deposition of critical nutrients and toxins in many regions of the Northern Hemisphere.

The observed changes in the chemical composition of the troposphere and stratosphere are having adverse effects on human enterprises, including agriculture and human health; they also affect the productivity of natural ecosystems and have increased the radiative forcing of climate.

In the last decades, global change research has been successful in leading to a scientific understanding of a number of these changes. For example, the well-documented year-by-year increases in CO₂ have led us to recognize the ability of humans to perturb the global Earth system through combustion of fossil fuel and deforestation. In addition, the Antarctic ozone hole was discovered and diagnosed, and its cause is now largely understood to be the emission of halocarbons. These advances occurred because of the existence of a strong research capability in observations, theory, and laboratory studies that could be focused rapidly on these problems. Nevertheless, major scientific problems involving changes in atmospheric composition remain to be resolved. For example, the role of marine versus terrestrial systems in the uptake of anthropogenic CO₂ is not yet understood. Understanding of the balance between the two is required to project future CO₂ abundances in the atmosphere. Similarly, the understanding of ozone changes in the lower stratosphere and troposphere is incomplete and yet is essential to comprehend the relative importance of the various causes of climate change.

Among the key scientific questions are the following:

1. Although the processes responsible for the formation of the Antarctic ozone hole are largely identified, we need to understand why the observed ozone depletion at midlatitudes in the lower stratosphere is greater than that derived from chemical models. A better understanding is important to predict future changes in the level of ultraviolet-B (UV-B) radiation at the Earth's surface over the next 10 years during which the maximum ozone losses will occur.
2. Although the global increases of trace gases such as CO₂ and CH₄ are well documented, we must assess the relative role of fossil fuels, land cover change, and natural ecosystems in controlling those patterns in order to accurately project trends into the future.

3. Although we understand the reason for the high levels of ozone over several regions of the world, we need to better establish the distribution of ozone in the troposphere in order to document and understand the changes in the abundance of global tropospheric ozone. This information is needed to quantify the contribution of ozone to the Earth's radiative balance and to understand potential impacts on the health of the biosphere.
4. Having recognized the importance of particles in the chemistry of the stratosphere, we must determine how aerosols and clouds affect the chemical processes in the troposphere. This understanding is essential to predict the chemical composition of the atmosphere and to assess the resulting radiative forcing effects in the climate system.
5. Finally, we must determine if the self-cleansing chemistry of the atmosphere is changing as a result of human activities. This information is required to predict the rate at which pollutants are removed from the atmosphere.

To address these questions, the coordinated research strategy based on observations, laboratory studies, and modeling needs to be sustained and judiciously focused. Surface-based observations of chemical concentrations are the key to long-term monitoring of chemical changes in the atmosphere. Similarly, measurements of exchanges among the terrestrial ecosystems, oceans, and the atmosphere are critical for understanding the inputs to and removal of chemical species from the atmosphere. Airborne measurements provide insights into the specific processes occurring at various levels of the atmosphere. Observations from space are the only practical way to provide global coverage of the atmosphere. Laboratory studies provide the fundamental information on the chemical reactivities of atmospheric species. Modeling provides a comprehensive statement of our understanding and is needed for the interpretation of global observations and the prediction of future changes.

Satellites have been essential for the global observation of ozone and other chemical species in the stratosphere and for our assessment of ozone trends, particularly in the Southern Hemisphere, where ground-based stations are sparse. Satellite observations of terrestrial ecosystems and the ocean have also been used to characterize their interactions with the atmosphere and hence their influence on its chemistry. Likewise, meteorological observations have been essential for developing chemical transport models. Space-borne observations will continue to be a necessary component of the observational program.

This coordinated research strategy is supported by contributions from several federal agencies, and the research is carried out in universities, federal laboratories, and the private sector. Maintenance of these capabilities is the most cost-effective strategy for addressing both the recognized and the unforeseen problems of the future related to the chemistry of the atmosphere.

These capabilities and research strategy have been built into the plans of the U.S. Global Change Research Program (USGCRP) and also those of the international scientific community as represented by the International Global Atmospheric Chemistry Program (IGAC) of the International Geosphere-Biosphere Program (IGBP) and the Stratospheric Processes and Their

Role in Climate (SPARC) Project of the World Climate Research Program (WCRP). Activities are being carried out to support international conventions and assessments of ozone and greenhouse gases.

The Earth Observing System (EOS) space program will provide important measurements to address global change issues related to atmospheric chemistry (e.g., lower-stratospheric composition). Not all key information, however, can be gathered from space (e.g., reactive nitrogen budget in the troposphere), and are required observations from other types of platform. Both components are necessary.

Observing Strategy

In addition to maintaining the above research strategy of field and laboratory process studies, monitoring, and modeling investigations, we conclude that the following specific foci are needed in an observing strategy:

Stratospheric Ozone and Other Chemical Compounds

The continued operation of TOMS-like and SBUV-like instruments is needed to determine future trends in the total ozone column abundance. It would be useful, however, to coordinate efforts at the international level, since similar measurements will be performed in Europe (e.g., GOME and later OMI) and in Japan. In order to address the most pressing scientific questions (e.g., processes affecting the evolution of ozone in the lower stratosphere), it is also important that SAGE, MLS, HIRDLS, and TES be implemented and launched as soon as possible. Among several important observed quantities, SAGE will provide information on the global distribution of aerosols and their size distribution (key to our understanding of heterogeneous chemical processes) and their variation resulting from potential future volcanic eruptions. MLS will provide global coverage of the abundance of reactive chlorine (key to assessing ozone depletion, especially in polar regions). HIRDLS will observe at high spatial resolution the distribution of ozone, several other molecules, and aerosols in the lower stratosphere and upper troposphere. This will be key to verifying chemical transport models and providing for the first time global observations of chemical and radiatively active compounds in the upper troposphere and lower stratosphere. TES will measure tropospheric ozone and provide information on its precursors.

The continued operations of field campaigns using aircraft such as the ER-2 and DC-8 National Aeronautics and Space Administration (NASA), the P-3 National Oceanic and Atmospheric Administration (NOAA), and the WB-57 National Science Foundation; ground-based observations using a variety of techniques; and balloon-borne instruments are essential to ensure a solid base of observational data in the next decade. In addition, it is essential that the observations be integrated into theoretical modeling studies.

Tropospheric Ozone and Other Chemical Compounds

To obtain essential information on the global distribution of ozone and to understand the processes responsible for changes in its abundance, the recommended strategy should involve the following simultaneous actions:

1. Extend the existing (but very limited) ozone network, which ideally should include on the order of 50 stations judiciously distributed worldwide, and provide ozone sounding and lidar observations on a regular basis.
2. Develop a TES instrument focusing on tropospheric ozone and other species that affect tropospheric ozone concentrations to work in conjunction with the international ozone network.
3. Conduct a number of in situ airborne campaigns designed to investigate the chemical and physical processes that affect ozone in the global troposphere. Several ongoing and planned regional studies can contribute to this global effort.
4. Integrate the above observations into complementary laboratory studies and theoretical modeling and interpretation.

As currently planned, MOPITT on EOS AM-1, which measures the global distribution of carbon monoxide, and hence provides information on tropospheric intercontinental transport and on biosphere-atmosphere interactions, is the only space experiment in the U.S. program addressing questions of atmospheric chemistry that will be launched before the next century.

Tropospheric Aerosols

Although it has been suggested that aerosols in the troposphere play a significant role in climate forcing, the quantification of this forcing has been hampered by a large number of uncertainties (e.g., aerosol mass scattering efficiencies, chemical and optical properties, formation processes). These questions will best be addressed through field campaigns, augmented by laboratory and modeling studies, and by "closure" studies conducted from aircraft or balloons and from surface stations.

Space observations will provide aerosol climatologies needed to calculate the radiative forcing, using a combination of AVHRR and SeaWiFS, augmented with data from POLDER (a French instrument flying on a Japanese satellite) and GOME (on ERS-2). Lidars on free-flyers will be very useful to gather information over both land and oceans.

CONCLUSION

In the scientific subject areas described in this appendix, information should be provided through appropriate international scientific assessments that describe and evaluate research results. The research and assessment plan delineated here would provide end-to-end service to the nation on key issues relating to atmospheric chemistry and must involve all scientific stakeholders. Just as atmospheric chemistry has provided timely information to decision makers in industry, government, and the public on stratospheric ozone change, so too can this research program continue to serve the nation's current and future information needs in this area.

C

ECOSYSTEMS

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WORKING GROUP SUMMARY

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Large-scale ecosystem studies are a rapidly maturing field of science, which under the impetus of global change research has had major successes over the past decade. Improvements in fundamental understanding of marine and terrestrial ecosystems and hydrology have already led to practical applications in weather and climate modeling, air quality, and improved water resources; forest, fisheries, and rangeland management; and natural hazards responses.

The principal questions in large-scale ecosystem science involve understanding the effects of changing land cover on land-atmosphere exchanges of carbon dioxide (CO₂), water, and energy, and consequent effects on climate and the carbon cycle. The synergistic instrument complement of the Earth Observing System (EOS) AM-1 and PM-1 platforms, combined with data from Landsat and other ocean-sensing satellites to document the roles of marine ecosystems in the carbon cycle, will satisfy in large measure the satellite data needs of the ecosystems community and will result in a massive improvement in the quality of remote observations.

Assessment and Future Requirements of the U.S. Global Change Research Program and the Mission to Planet Earth

Overall, the U.S. Global Change Research Program (USGCRP) has been successful in advancing the science and tools required for space-based assessment of ecosystem change. The ground- and ocean-based components of the program have had varying degrees of success. Elements linked to atmospheric science (biophysics and trace gases) have had the strongest programs. The more ecological (vegetation and land cover) and integrative (ecosystem manipulation experiments) components have been supported on an ad hoc basis. Extension of local understanding from process studies to regional and global scales requires modeling. This work has made major advances but is less well-developed than in situ or remote sensing aspects of the program. Fulfilling the goals of the USGCRP requires enhancement of integrative modeling and close coordination of modeling with ground-, ocean-, and space-based studies.

Areas of Success

- Field and theoretical studies have been carried out that have laid the foundation for understanding the role of vegetation and soils in weather and climate, and have advanced our methods for interpreting satellite data. Execution of the field experiments planned for the Mississippi and Amazon basins would complete this series of studies.

- Satellite observation techniques, ground-based observations, and models, have been developed that can determine changes in land cover type, as well as spatial and seasonal changes of vegetation.
- The role of nutrients in the large-scale interactions of ecosystems with the atmosphere has been elucidated. The effects of nutrients such as nitrogen and phosphorus now must be systematically incorporated into global models of land-atmosphere interactions.
- An ambitious program has been implemented to measure and model the sources and sinks of CO₂ and trace gases from biological and biomass-burning sources. This program will allow the development of an observing system to determine trends and patterns of emissions and uptake on continental scales.
- Oceanic time-series observations have revealed previously unknown year-to-year variations in coupled ocean biology, chemistry, and physics that are, linked to climate variability.
- Regional ocean carbon studies have quantified seasonal marine ecosystem effects on atmosphere-ocean CO₂ exchange and El Niño-related variations in the equatorial Pacific sources and sinks of CO₂.
- Impacts of climate change and variability on agricultural and forest ecosystems have been modeled.

Critical Work in Progress That Should Be Continued or Enhanced

- Experiments to determine the long-term ecosystem-level effects of rising CO₂ in forests and agricultural crops and grasslands have just begun; these experiments must be sustained and effectively linked to global change modeling efforts.
- Observations of atmospheric CO₂, its isotopes, and oxygen are crucial for quantifying processes within the carbon cycle, these measurements are at a minimal density for success and must be expanded over the continents.
- The ocean CO₂ survey must be completed, and associated modeling efforts enhanced, in order to fully assimilate this information into global climate models.

- The ability to determine land cover changes from space has been demonstrated in regional studies. Global implementation, including the expansion of international partnerships, is required.
- Regional case studies of human land cover change have begun. Efforts to understand how changes in population, technology, and development affect land cover must be developed and linked to global-scale models.

Several Areas Requiring Special Emphasis

- Great opportunity for understanding the role of ocean ecosystems in the global carbon cycle has been lost with the nearly decade-long hiatus in ocean color data. Launch of the SeaWiFS instrument must be given high priority.
- Data sets must be developed for the use, intercomparison, and testing of models of terrestrial vegetation and productivity.
- Preliminary exploration is necessary of the potential for emerging and possibly commercial satellite measurement technologies, especially for managed ecosystems such as agriculture and forests.
- Implementation of vegetation analysis transects, utilizing existing and new field studies, is required to characterize the large scale relationships among climate, vegetation, and human activity.

D

DECADAL TO CENTENNIAL CLIMATE

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WORKING GROUP SUMMARY

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The last decade of research has demonstrated two important points. First, significant climate variability on time scales of decades to centuries has occurred in the past and will likely continue into the future. Second, the potential exists for significant changes in climate and climate variability over the next decades to centuries in response to human activities.

Substantial advances in climate understanding and prediction have occurred over the last decade:

- There have been recognition and documentation of the scope of natural variability, involving (1) remarkable records of variability and rapid change from ice cores, tree rings, and corals; and (2) determination, by means of models, that ocean-atmosphere interactions can lead to significant variability on a variety of time scales.
- Calibrated five-year Earth Radiation Budget Experiment (ERBE) observations have documented that clouds have a net global radiative cooling effect on the Earth-atmosphere system by about 15 to 20 watts per square meter. The regional cloud forcing data have contributed significantly to diagnosing deficiencies in general-circulation model (GCM) treatment of cloud radiative interactions.
- Water vapor behavior and feedback analysis has been advanced on theoretical, observational, modeling, and methodological grounds.
- Understanding the role of volcanic eruptions as a climate forcing factor has been advanced, as evidenced by our ability to measure and examine the impact of recent eruptions (Mt. Pinatubo).
- The linkage of climate models with impact models on agriculture, water resources, ecosystems, and the economy, and quantification of the positive and negative effects of climate change and variability on agricultural production and water supply, have been substantially improved.

This research, however, has also underscored the complexities and uncertainties associated with detecting and projecting the nature of future climate change. For instance, a concern for anthropogenic global change cannot be dealt with in the absence of an adequate understanding and documentation of present and future climate and its natural variability on time scales of years to

centuries, as well as a quantified understanding of anthropogenic forcing itself. For anthropogenic forcing, we clearly need to determine the role of tropospheric aerosols and further elucidate of the carbon cycle.

Determination of the response to anthropogenic forcing is inseparable from understanding the natural system. This understanding ranges from solar and volcanic variability; to the feedbacks resulting from the interactions of water vapor, clouds, and radiation; to the massive heat fluxes associated with the motions of the air and oceans and the exchanges between them.

In short, changes in all the major factors that influence climate variability must be well described and their interactions understood. The evidence clearly shows that we must be able to couple the components of the Earth system, including the ocean, atmosphere, land, and ice, and describe major feedback processes in order to be able to reduce the uncertainties in describing the nature of future climate. The primary characteristics of the climate system must also be documented through consistent, long-term observations.

An understanding of both natural variability and anthropogenic global change is essential to address the wise use of resources, human health, agricultural productivity, and economic security. Improved global change predictions are central to these objectives and are key U.S. Global Change Research Program (USGCRP) research priorities. Addressing these complexities and uncertainties requires a comprehensive program. Each of the essential science elements listed below addresses uncertainties that currently hinder our ability to understand and predict future climate variability and change.

Essential Science Elements

1. USGCRP must characterize and determine the changes in the significant global change forcing factors (solar, carbon dioxide, other radiatively important gases, aerosols, land cover change) by means of continuous observation. Tropospheric aerosols are a major priority that have not been adequately addressed.
2. USGCRP must document global change (e.g., temperature, precipitation, ozone, air quality, ecosystems). Climate change requirements must be a part of current and future observational systems (including operational elements) and of satellite convergence efforts.
3. The identification and understanding of the natural variability of climate, including the historical and paleoclimatic record, must be a product of USGCRP efforts.
4. An ability to quantify the carbon cycle and its driving factors is essential for determining future atmospheric carbon dioxide levels.

5. USGCRP must have the combined observations, process studies, and modeling efforts necessary to address the issue of cloud-water vaporadiation feedback, which remains the major source of uncertainty in climate change predictions.
6. USGCRP efforts must be able to characterize the nature of the oceanic circulation, the surface fluxes of energy and moisture, and the ocean's natural variability.
7. USGCRP must have the combined observations, process studies, and modeling efforts necessary to address land-vegetation-atmosphere interactions.
8. It is essential to characterize and understand cryosphere (ice caps, sea ice, snow cover) responses to climate change.
9. USGCRP must include the basic science capabilities to address the impacts of global change on ecosystems, (e.g., forests and agriculture) and on water resources.
10. The critical economic, technological, and demographic trends that are affecting the ability of natural and human systems to cope with climate variability and change must be understood. These include changes in urban infrastructure, farming technologies, trade, and water use and efficiency--all of which can increase vulnerability or resilience to global change.

In reviewing the science elements above, all the major elements of the current program (e.g., Earth Observing System (EOS) measurement priorities, the National Oceanic and Atmospheric Administration (NOAA) climate research elements; the basic research components of the National Science Foundation; and the Department of Energy's ARM program) are essential. In fact, some of the elements (e.g., item 1,2,8, and 9 above) are currently not well addressed and must be enhanced. This must not occur at the expense of understanding basic features such as heat transfer by the oceans and atmosphere. There is little room for budget cuts in decade to century climate research without significant damage to critical science objectives. We, therefore, conclude that substantial budget reductions must come from other program elements, such as diverting savings from satellite convergence or increasing the efficiency of the EOS Data and Information System (EOSDIS). A multifaceted, balanced program that addresses each of these ten major science elements is essential so as not to have major gaps in our understanding that serve to limit both the utility of measurements and our predictive capability.

Issues of importance to the success of USGCRP are not restricted to addressing scientific priorities; a number of management issues, if addressed, would result in a stronger program. The field of global change research has had a history of significant progress and evolution involving integration of the essential components of research: data analysis, theory, and modeling. The maintenance and enhancement of progress demand a balanced approach. Intensive examination

of existing and future observations (in situ and remote), improved theory and modeling, the maintenance of existing and future measurements and calibrated monitoring, and the inclusion of climate considerations in the design of routine observations are required to satisfy crucial needs. Satellites offer unique capacity for global coverage and monitoring, and in situ measurements offer unique capacity for validation and for addressing critical details.

Essential Programmatic Changes

1. USGCRP must not be considered a collection of quasi-independent activities, although some independent efforts are necessary for creative opportunity. Nevertheless, the larger components must be managed as a set of serious scientific programs requiring continuous oversight, connectivity, and continuity across agencies; resource allocations and goals must be adjusted in light of developing knowledge and budget changes.
2. A scientifically and financially balanced program is essential, with strong components spanning in situ observations, satellite observations, process studies, and integrative modeling. The present management limits such balance.
3. The United States must enhance the linkages between national and international programs. However, the United States has become an untrustworthy international partner. Enhancement requires greater integration, which is difficult without stronger U.S. long-term commitment.
4. USGCRP must have the flexibility to include exploratory efforts. Part of the strength of a robust program involves opportunities for innovative inquiry by individual investigators and a capacity to address new issues.

E

**ASSESSMENT OF NASA'S
MISSION TO PLANET EARTH/EARTH OBSERVING SYSTEM (MTPE/EOS)**

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EOS's program structure and science have been significantly improved. Its research is thoroughly peer reviewed by excellent, independent academic science teams with strong inputs from a wide range of respected scientists. The results of those reviews are routinely communicated to and acted on by the appropriate levels of the National Aeronautics and Space Administration (NASA) and the U.S. Global Change Research Program (USGCRP).

EOS provides unique information for the execution of required global assessments. Current sensors and platforms are appropriate and efficient. EOS sensors correctly reflect the Earth system science priorities that can be measured effectively with existing sensors and give proper emphasis to the development of sensors for other important phenomena. Areas in which change is needed are recognized and are being addressed. One is the need for properly documenting global change. Current sensors reflect an earlier emphasis on process studies. A rigorous dynamic calibration and validation program is essential for maintaining the dynamic continuity of critical long-term measurements through successive generations of sensors. Fortunately, EOS sensors are designed for high calibration.

EOS is properly configured for science and programmatic resilience. NASA has significantly increased opportunities for the introduction of advanced technology through experiments such as Lewis and Clark and through continuing science programs such as the Earth System Science Pathfinder (ESSP). It has become increasingly open to the infusion of technology from the Department of Defense (DoD) and industrial programs, which have significantly strengthened EOS.

Observing system priorities remain consistent with those of the USGCRP and the four MTPE science areas, which require ground and in situ measurements. Significant, rapid change has required and produced significant learning, but the broad, continuous EOS data sets remain relevant. The need for new measurements (e.g., tropospheric wind and aerosols, soil moisture) has become apparent and has stimulated productive thought on new means to measure them, perhaps from small satellites. It has also stimulated thought on new ways to perform key measurements such as lightweight synthetic aperture radars (SARs), hyperspectral sensors, and tropospheric chemistry sensors.

The current range of scientific uncertainties makes EOS's broad range of measurements relevant--particularly in that its sensors emphasize the validation, calibration, and continuity required for the detection of subtle climate signals. EOS supports a wide variety of societally relevant assessment programs and applications such as deforestation, agriculture, and water resources and quality. It addresses these priorities in cooperation with ground-based and in situ sensors. Current efforts include a productive mix of space, in situ, and ground measurements through a proper blend of agency contributions. The detailed correlation of space sensor capabilities with current science area priorities could be usefully addressed by a longer study.

Technological opportunities are being pursued aggressively. There is a sound process for the design of sensors with the performance and calibration required for measurements of the quality required for global change research. That process proceeds from requirements, through technology and trades, to sensor designs, in which size is properly seen as a dependent variable. EOS sensors use best current technologies and calibration methods--including those of DoD--to optimize performance. EOS is now the principal driver of sensor technology and research. Although it is fairly new and not fully activated, there is now a process for the incorporation of other emerging technologies, as well as established vehicles for the importation of technologies developed for other purposes by DoD and industry. There is adequate launch capability in existence or development for satellites of all sizes. All are affordable, although the cost per kilogram of payload is about a factor of three higher for small launchers than for launchers in the Delta class, as is designing spacecraft for compatibility with several launch vehicles to reduce sensitivity to launch losses at modest cost and performance penalties.

We can now build capable satellites of any desired size effectively; their performance domains are evolving rapidly. We now understand better when it is possible and appropriate to distribute sensors over many satellites. It is also better understood when various technologies should be used (e.g., technologies developed by DoD appear applicable to laser aerosol measurements, but not to spectral measurements, for which they currently lack calibration). It is also understood how efforts such as the New Millennium Program (NMP) can address bus costs, but not usefully substitute for operational buses or reduce system costs, which NMP does not address.

Small satellites promise low spacecraft costs and short schedules--typically one to two years from conception to flight. They provide mission and programmatic flexibility, which are important in stimulating innovation. Formation flying may also enable their use in replacing failed instruments or in maintaining dynamic continuity of measurements when introducing new sensors. Small satellites are currently best suited for focused missions of narrow scope. They are not universally applicable to the current generation of EOS sensors, many of which are too heavy or too large for small satellites. Life-cycle costs (sensors, satellites, launch, mission operations, and data acquisition) are not necessarily reduced by replacing the current multisensor medium-sized satellites with many small satellites for the deployment of a full suite of high-quality, calibrated sensors. Advances in technology, such as may come from the ESSP, NMP, and other sources, might alter this conclusion within the next few decades.

Data continuity is essential for meaningful scientific results. Space programs such as NASA's Landsat have successfully produced long-term records of key parameters, although not with the calibration desired by the climate research community. EOS will fly well-calibrated radiation, tropospheric water vapor, and aerosol sensors, as well as a series of Moderate Resolution Imaging Spectroradiometer (MODIS) instruments for the cloud feedback studies suggested by the Marshall Institute and others. As the latter have, long-term programmatic stability is essential for the success of these studies. To extend the studies of physical climate effects to global change, which is more complex, requires measurements over oceans and land--

hence their inclusion in EOS. It is unlikely that a narrowly focused study would provide satisfactory long-term answers to these questions.

Convergence opportunities offer the promise of reduced overlap, reduced cost, and improved science through NASA, National Oceanic and Atmospheric Administration (NOAA), and DoD cooperation on weather and climate satellites. There are significant institutional barriers and technical issues that could impede such convergence, but the payoff is so great that it justifies extensive study. If operational instruments were calibrated to research standards, a wide community of users would benefit. Much the same can be said for multiuse (science, operational, military, commercial, and international) missions on common platforms. Such developments have been strongly resisted because of cost, interference, and regulatory concerns, although these arguments are becoming less relevant while the potential savings are increasing.

There is a long, successful history of international cooperation in Earth observation. Many nations are providing satellites and sensors that form an essential part of the MTPE program. European and Japanese sensors will fly on NASA satellites and vice versa. Data exchange agreements are being implemented among these partners and others to maximize their value to the overall community. Many of EOS's sensors are provided by international partners; they are coordinated through EOS-ESA (European Space Agency) sensor discussions; and Europe, Japan, and Canada will provide EOS ground segments. In operational systems, NOAA polar orbiters carry important donated foreign instruments, and Europe's EUMETSAT will assume responsibility for one of NOAA's traditional satellite flights near the turn of the century. When one of the U.S. Geostationary Operational Environmental Satellite (GOES) geostationary weather satellites failed, EUMETSAT provided one of its satellites to prevent data loss for the critical Atlantic seaboard.

These international arrangements are voluntary and exercised primarily through the Committee on Earth Observation Satellites (CEOS). Reliance on such mechanisms leaves the United States with no fall-back position in the event of default, although U.S. reliability has been most in question of late because of issues such as Topex-Poseidon. It would be useful to isolate EOS from current political issues. At present, the United States has limited ability to affect these arrangements because of the inability to make multiyear commitments. There could be significant benefits from being able to address reliability by entering into multiyear commitments on satellites, sensors, and global observing systems.

Innovative approaches to data collection and management may offer significant savings. Data purchases still appear attractive and useful, despite recent experiences with SeaWIFS. However, the government would have to enter into long-term contracts to stabilize purchases sufficiently to secure the interest of industry. Commercial activities and opportunities for sensors on commercial constellations such as Teledesic and IRIDIUM are uncertain. There has been only limited contact and discussion, and industry reception to date has been characterized as not very positive. That is understandable. The market is very uncertain. Only the upper limit of the estimates of its magnitude would approach the cash flows involved in those systems; anything less would be viewed as a hindrance to their rapid deployment. In any case, communication satellites

do not use polar sun-synchronous orbits; the radiometric correction of data taken from their orbits does not appear feasible.

Applications of EOS data are much greater than those of previous Earth sensing satellites. For agriculture, Landsat-7 offers a major improvement in the measurement of crops, and the AM and PM (morning and afternoon equator crossing) platforms will significantly improve measurements of vegetation and moisture. For land use, Landsat-7 will greatly improve surveys of biodiversity, and AM will improve the precision of maps. For seismology, AM will document changes in land surface and volcanism. For hydrology, radars will improve topography and El Niño/Southern Oscillation measurements; lasers will measure ice; and AM and PM will significantly improve understanding of cloud dynamics and cover. For mapping, AM will provide digital elevation; lasers will give ice and land elevation. For national security, Landsat-7 will greatly improve the type of global surveillance provided for the Gulf War; AM will improve map resolution; and PM will give the moisture measurements needed for force mobility analyses. All of these improvements will be of significance for both civil and commercial applications.

Program Impact Issues

Restructuring has protected the EOS program and increased its resilience, but that process has reached its limit. Significant reductions in annual or aggregate budgets or imposed constraints on technical options could result in elimination of key sensors or platforms, slippage of schedules, loss of continuity in data sets, or elimination of the mechanisms for promoting the innovation needed for downstream cost reductions and science improvements. A premature shift to small platforms could eliminate key measurements.

Summary

EOS's science and program are valuable, unique, and resilient. It would be appropriate to reduce its reviews to regular but less frequent intervals. Its space observation program has appropriate balance internally, but needs to be balanced with ground and in situ measurement across all of the USGCRP priorities. EOS priorities are evolving and open to technological innovation. Its sensors are well designed and calibrated. Given long-term program stability, they should be able to provide the quality of continuous measurements of radiation, vapor, aerosol, and cloud feedback necessary to understand and document climate change.

EOS is open to the introduction of technology from research, DoD, and commerce. Adequate launch and fabrication capability exists for satellites of all sizes. Small satellites offer flexibility and rapid innovation--at a penalty in cost. However, it should be possible to use them effectively to perform rapid tests of new sensors for key parameters such as tropospheric winds, aerosols, and soil moisture, among others.

Convergence offers significant advantages and savings domestically and internationally. Impediments to the convergence of domestic programs, which are largely institutional, could profit from more careful study and definition. International collaboration has a long, successful history. Current impediments, which are produced in part by the voluntary nature of these collaborations, could be improved by multiyear commitments. EOS data will have significantly greater value for civil, commercial, and defense applications than the data from previous lower-resolution sensors. These applications alone could justify maintaining EOS's schedule. However, although the EOS program remains resilient, it is now stretched to its limits. Further reductions or constraints could reduce its technical capabilities and delay or eliminate those advances.

F

THE EARTH SCIENCES INFORMATION SYSTEM

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The Earth Observing System Data and Information System (EOSDIS) is a central component of the EOS program for linking observations made from space with those obtained on the ground and assisting scientists to convert them into enhanced understanding of the Earth system and the processes that drive its evolution. EOSDIS must be designed and implemented so that the investment in EOS space observations is multiplied many times through revealing analyses, through new models of the Earth system and its components, and through stimulation of a wide range of educational and economic activities. The EOS program, and indeed the entire U.S. Global Change Research Program (USGCRP), cannot be successful unless EOSDIS fulfills expectations that it will empower new levels of achievement in the Earth sciences and applications, and in a wide range of activities in both the public and the private sectors.

To meet these expectations, we must now embrace a revolutionary expansion of the conceptual model that governs the management and operation of the system by affording the scientific community full partnership with shared responsibility. If we create and commit ourselves to the right model, all of the details related to design and technology will fall into place readily. Moreover, a new and successful model for EOSDIS, and by extension for USGCRP as a whole, will provide a stimulus for new approaches to data and information management in a wide variety of activities and will broadly benefit the nation.

The two key requirements for the system are that it must

1. utilize an open management approach in which key decisions are made with community leadership, and assignment of responsibilities is based on peer review; and
2. encourage innovation and creativity through wide participation of the scientific, public, and private sectors.

The revolution proposed in the management and implementation of EOSDIS will prove successful only if it incorporates, from the beginning, powerful incentives and meaningful criteria. As criteria for evaluating the design and implementation, that the new concept should ensure that

- users can readily locate data sets with real and valuable scientific content;
- users can access and utilize such data sets readily and in a timely fashion;
- collaborative analysis and research is stimulated and encouraged; and

- demonstrable progress in scientific endeavors and in applications to other activities is evident.

To provide incentives for the scientific community, the system must enable and encourage scientists and scientific teams to use it for interaction and as a form of electronic publication and dissemination of their results.

Historical Background of EOSDIS

The EOSDIS was conceived a decade ago by the science steering groups that developed the initial plans for EOS as a powerful, distributed data and information system that would provide ready access to the data and stimulate new levels of scientific creativity and collaboration in studying the wide range of interdisciplinary issues that must be resolved to understand the evolution of the Earth system.

However, the system design developed in good faith by the National Aeronautics and Space Administration (NASA) was shaped and constrained by the engineering protocols then in vogue for the development of large and complex hardware systems. Thus, the initial architecture proposed by NASA was to be centrally controlled and operated to ensure that it met ambitious performance and reliability requirements. Later versions developed in response to the objections and advice of the scientific community retained these features. The architecture required by NASA in the initial contract with Hughes Applied Information Systems (HAIS) generated considerable concern and was revised after a thorough National Research Council (NRC), 1994 review that produced recommendations for a logically distributed system, based on a client-server model, that would accommodate evolving computer system concepts and technology. Despite the notable improvements in architecture and concept introduced by HAIS in response to NRC recommendations, the current design and performance requirements, the system of multiple Distributed Active Archive Centers (DAACs) (each configured as a stand-alone, high-performance, and highly reliable computing center), and an extensive engineering and management superstructure are stressing the bounds of affordability (see Table 1).

Still, considerable progress has been made. This new client-server architecture of EOSDIS takes advantage of logical distribution and modularity and will allow the system to evolve as both computer system concepts and technology advance in the years ahead. The system now can take advantage of the concepts of the World Wide Web (WWW), the continuing advances in computer and storage capabilities, and the advantages conferred by developing a set of permissive standards appropriate to global change research that will enable and encourage wide access to EOSDIS and wide use of, and contribution to, its resources. Thus, with appropriate incentives, the system can be flexible and quick to adapt to a rapidly changing environment.

TABLE 1.1 EOSDIS Components and Costs (FY 1991-2000)--NASA Concept

Components	Cost (\$ million)
Flight and Data Operations	
Flight operations and spacecraft control	86
Ground stations (communication with spacecraft)	50
EOS data and operations system (data capture and initial processing)	225
EOSDIS backbone network (transmit data to DAACs)	106
Distributed active archive centers (preparation of data products)	1,021
Distribution of data to users via Internet	52
System Engineering and Management	
System engineering and integration	372
Program and project management	74
Related science support	144
TOTAL	2,230

A New Concept: The Earth Sciences Information System

The present plans for the development of EOSDIS have been widely criticized for reasons ranging from an apparently excessive cost to lack of a governance structure that engages and empowers the scientific community. A number of observers do not believe that problems with the system can be eliminated by engineering redesign. Instead, the concerns are much more fundamental and are related to the basic management approach--to the conceptual model that has guided and constrained the management and engineering of EOSDIS.

Thus, a new model is proposed that will distribute many of the functions of the system to a wide range of government, academic, and private organizations through a competitive process. To distinguish this new model from those of the past, will be referred to it as the Earth Sciences Information System (ESIS). The basic concept is illustrated in Figure F-1. The functions shown

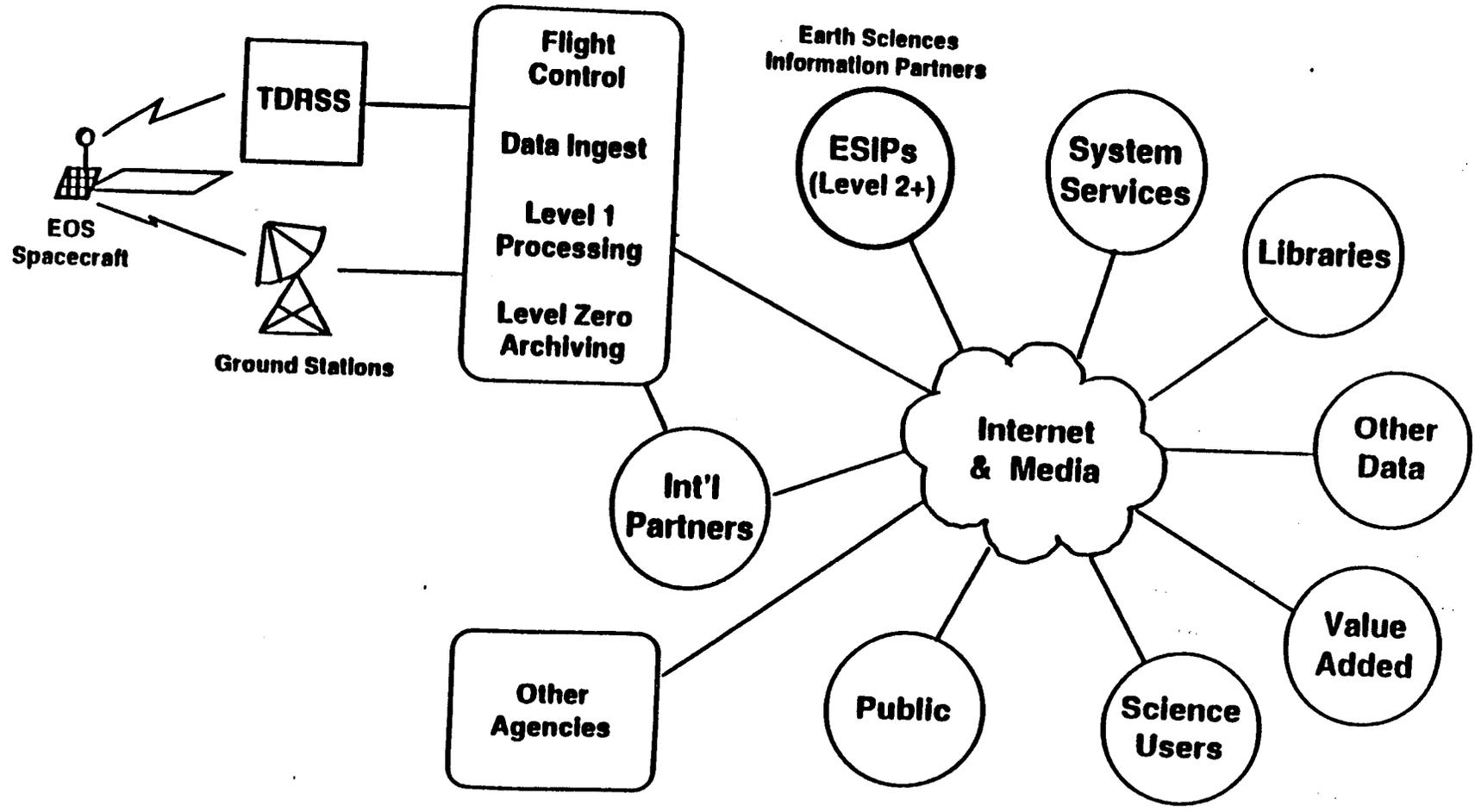


FIGURE F-1 Earth Sciences Information System

on the left--flight control, data receipt and Level-0¹ archive, and initial processing of the of the data through Level 1--will follow the existing EOSDIS model. Although the model for this part of the system does not change, that these functions can be streamlined considerably with important reductions in cost.

On the right, the generation of products and the combination of initial products into a wide range of scientific data fields would be opened to a competitive process through an Announcement of Opportunity, with bidders allowed to bid on any number and combination of products and services. It may be anticipated that the successful bidders will include NASA laboratories (perhaps some of the present DAACs), teams of EOS investigators, other academic collaborators, and private sector organizations and firms. These entities are referred to as NASA Earth Science Information Partners (ESIP) and it is anticipated that similar organizations will develop outside of NASA sponsorship or supervision. Thus, ESIS will become a privatized, market-driven federation of product generation and enhancement capabilities. Rather than a centrally managed entity, it will become a coordinated activity, drawing in new participants.

The effectiveness of NASA ESIPs will be determined by the criteria used to evaluate both proposals and continuing performance. Three are recommended:

1. timely production of specific scientifically meaningful products;
2. provision of effective user support and appropriate data access; and
3. formatting data sets and associated documentation in a form suitable for transmission to permanent libraries.

¹ Definitions of Data Levels (Adapted from the MTPE EOS Reference Handbook, NASA/Goddard Space Flight Center, 1995)

Level-0 - Reconstructed, unprocessed instrument data at full resolution

Level-1A - Level-0 data with ancillary information including time, geo-location, and calibration coefficients.

Level-1B - Level-1A data processed to sensor units (if applicable)

Level-2 - Derived geophysical variables at the same resolution and location as Level-1 source data

Level-3 - Variables mapped on uniform space-time grids, usually with some completeness and consistency

Level-4 - Model output or results from analyses of lower level data, including variables derived from two or more measurement

Introducing competition will have important consequences. The first is that bid prices will be consistent with the marginal cost of providing actual ESIS services and thus can be presumed to be considerably less than the cost of dedicated, stand-alone facilities. Second, the new model is intellectually inclusive and will attract new participants, creating a much broader and more effective process for attacking the key problems of global change research. Third, with the development of standards and protocols to interchange data sets on Internet and WWW, ESIS will create a new capability of broad value to the scientific community and the private sector and thus to the entire nation.

With suitable extensions of the catalogs and advertising services being developed by HAIS, the results of EOS research will be available to all Internet users. This, too, has important consequences. First, with appropriate standards, a wide range of scientists and scientific facilities that use EOS data will be encouraged to make their results available to others by conforming to system standards and thus publishing them electronically. Second, a market for ESIS services will develop in which value-added concerns will offer search, browse, and data delivery services that are extensions of the basic capabilities. Such services may be especially attractive to private sector users of EOS results and to schools and colleges.

Issues, Challenges, and Risks

The most evident logical difference in the two models is that responsibility for processing and product generation at Levels 3 and higher has been transferred from designated government facilities to the federation of community entities. In this section, we provide a preliminary view of some of the consequences is provided.

A variety of issues and risks are common to all computer systems and all endeavors in scientific data management. These include archiving, security, providing user assistance, and documenting user activities. Preliminary study, leads to the conclusion that, except for minor variations, these are essentially similar in the two models. Successful bidders will have to demonstrate that they understand these issues and have adequate and rigorous plans for dealing with them.

The proposed model for ESIS does pose new issues, however. The first is that of managing collaboration in a competitive environment. Developing, processing, maintaining, and improving EOS scientific products will require collaboration between the instrument teams or investigators. Moreover, the strong interdependencies of some data sets will mandate effective collaboration and careful scheduling. The Announcement of Opportunity must provide for arrangements that will encourage the necessary collaboration and include initial provisions or a negotiation phase to permit instrument teams to explore collaboration with several bidders or an otherwise successful bidder.

Moreover, even in the proposed decentralized and federated systems, a number of specific functions will require centralized intellectual leadership, an example being definition of standards

for metadata and supporting documentation. Further elaboration of these should take place in later stages of this review.

A second and critical issue is the governance of the new ESIS system. A significant advantage of the proposed model is its potential to stimulate the collaboration and wide participation of the scientific community in the processing and refinement of EOS products and in the development of higher-order products that reveal new aspects of an improving scientific understanding of the Earth system. To achieve this potential, the system must be responsive to users and participants--it cannot be centrally managed from the top down but must be governed as a federation of collaborating entities. Moreover, the federation must expand to include other agencies and the research teams they support. A 1995 NRC report sets forth the basic structure of such a federation in the context of managing scientific data (NRC, 1995).

A third issue is that the transition to the new system must be very sensitive to the expectations of international partners and the commitments that have been made to them. Agreements in place must not be jeopardized and should be modified only with the enthusiastic concurrence of these partners, many of whom may prefer ESIS capabilities to the present plan.

A fourth issue is whether reassessment and relaxation of system performance and reliability requirements will produce significant savings in total costs. Current requirements derive from the spacecraft data production rates and are designed to reduce risks to the central facility. With adoption of the ESIS model, the risks are transformed into those associated with scientific research, and tolerance for central risk can be increased. For data products deriving from the AM-1 platform, the transition will have to be handled with particular care because of complex interdependencies and tight schedules.

Finally, the success of either model depends in part on the continued viability of the Internet as a mechanism for high-bandwidth computer-to-computer communication. Bidders would have to demonstrate the commitment of their host organizations to maintain Internet connections of sufficient bandwidth. Although the advancing capabilities of the Internet or other national high-performance computer communication capabilities are expected to keep pace with demands for service, there is a risk that they may not. A first complication would be inadequate bandwidth to support the interactive processing of interdependent products; such a difficulty could be ameliorated by transfer of data on physical media via overnight delivery. A second complication would be charges for Internet services, a development that would lead to complications for scientific research that extend far beyond EOS. Such complications would be equally problematic in both models.

Transition to the New Model

The ESIS model will create a data and information system that operates differently from the present concept and will require that the transition be carefully managed. The most important action now is to adopt the new intellectual concept for the system and be clear about our long-term

goals. Every attempt should be made to put as much of the new system as possible in place before the launch of EOS AM-1. To do so, NASA, EOS investigators, and EOSDIS contractors must begin immediately to conduct a collaborative study of the implementation and cost of the federated system and to develop a plan for an effective, streamlined central management and engineering capability. Some representative actions typical of those required in such a study are listed in the next section. Although such a study may demonstrate that a gradual or incremental transition to the new system is advisable, we argue that the initial effort should be directed toward effecting a dramatic break with the past and creating an entirely new and contemporary federated management and operation of ESIS.

Recommendations

The following two recommendations summarize the discussion in this appendix:

Recommendation 1

- The components of the EOSDIS now under development for flight control, data downlink, and initial processing should be retained, but streamlined.

Representative Actions to Respond to Recommendation 1

1. Assess rigorously the relative costs of transmitting and receiving EOS spacecraft data with and without the Tracking Data Relay Satellite System (TDRSS).
2. Reevaluate EOS Data and Operations System (EDOS) functions with the aim of incorporating advanced technologies and limiting the scope to that needed for data capture and processing to Level-0. Reduce initial data processing costs by utilizing receiving stations for Level-0 processing and existing capacity at DAACs (e.g., at Goddard and EROS Data Center) for Level-0 to Level-1 or Level-2 processing.
3. Explore with end-to-end system plans the use of advanced technologies and concepts such as solid-state spacecraft data recorders, increased spacecraft autonomy, and contemporary data packet protocols to simplify data operations and reduce overall costs.
4. Explore replacement of the EOSDIS Backbone Network with commercial facilities to reduce engineering and continuing management costs.
5. Evaluate possible advantages and relative short-term and long-term cost savings

associated with development of a unique flight operations system for each mission in order to take maximum advantage of new capabilities, new technologies, and lessons learned from previous missions.

Recommendation 2

- Responsibility for product generation and publication and for user services should be transferred to a federation of partners selected through a competitive process open to all.
- To effect this recommendation, it will be necessary to examine the systems implications of reconfiguring EOSDIS as a loosely-coupled federation of quasi-autonomous partner organizations, each with a contractual obligation to perform a subset of the tasks involved in preparing and distributing scientifically reliable products at Level-2 and higher, identifying in particular those functions or services to the federation that must be provided centrally and those for which responsibility can be delegated to the partners.

Representative Actions to Respond to Recommendation 2

1. Reassess schedule, continuity, and reliability requirements for standard data products with the aim of simplifying preparation of the scientific data products, and thus reducing costs. Examine with EOS investigators and other potential users the hypothesis that only Level-0 data must be treated in a rigorous production sense.
2. Assess rigorously the advantages, disadvantages, and relative costs of moving Level-1 or Level-2 data to a distributed system of scientific data processing partners via Internet, commercial surface and space-based communication networks, or overnight delivery of media.
3. Obtain (from EOS instrument Principal Investigators and teams, other investigators, and an appropriate subset of existing DAACs) realistic cost estimates for preparing representative scientific data products in distributed processing units.
4. Develop prototype models of minimum machine-independent data format standards and interchange protocols that will facilitate exchange, interactive use, and electronic publication of EOS scientific data sets over existing commercial and Internet facilities. This effort should engage experts from the academic and commercial computer science communities and should concentrate on whether extensions to existing standards, such as those used on Internet and World Wide Web, are necessary or advisable.

5. Develop prototype protocols for peer review and signed electronic publication of scientific data sets that would provide incentives and quality control motivations to producers of these data sets.
6. Explore the use of information search facilities modeled on those now in use on the World Wide Web as a means of providing users with data search and access capabilities; explore whether the EOSDIS Version 1 and Version 2 systems could operate exclusively over the Internet (or anticipated national high-performance computer communications networks) to facilitate data exchange by scientists and to provide search and access capabilities to users.
7. Explore possible advantages of dividing EOS data into categories in order to determine the most effective means of processing and distributing data to users. Possible categories (and possible data producers) include operational data for other agencies (many possible producers, depending on timeliness), data of use to a limited community of scientists (instrument teams or Principal Investigators), data of wider scientific use (many possible producers), data of interest to educational institutions and the public (scientific or commercial data facilities), and data with commercial value (commercial or academic bidders).
8. Develop a preliminary model of a procurement process and an Announcement of Opportunity that could be used to solicit proposals from potential participants in a distributed scientific data processing system.
9. Develop a plan and realistic cost estimates, using the information generated by the above actions, for a distributed data processing federation as envisioned in Figure F-1, and seek the comments and advice of EOS investigators and the broader scientific and other user communities.

CONCLUSION

The proposal made here for creating ESIS offers many advantages to the government and the scientific community. Rather than being managed top-down by the government, the new model will create a federation of participants. By taking advantage of Internet capabilities, it will extend access to EOS results to a wide audience, including new participants in the private sector. Although substantial savings may be expected, the costs of the new approach can be estimated only after careful study.

Most significantly, it will stimulate participation of the scientific community in the governance of ESIS and create an entirely new system that can be the model and foundation for

the broader Global Change Data and Information System. Perhaps its greatest benefit, however, will be that it will generate a new approach to the interactive management and use of distributed data sets and, with an appropriate set of standards and protocols, provide a new capability of significant benefit to a nation increasingly dependent on collaborative and innovative exploitation of complex arrays of data and information.

The proposed new approach has substantial benefits and some challenging risks. However, the benefits envisioned more than compensate for those risks.

REFERENCES

National Research Council (NRC). 1994. Final Report. Panel to Review EOSDIS Plans. National Academy Press. Washington, D.C.

National Research Council (NRC). 1995. Preserving Scientific Data on Our Physical Universe: A New Strategy for Archiving the Nation's Scientific Information Resources. National Academy Press. Washington, D.C.

G

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