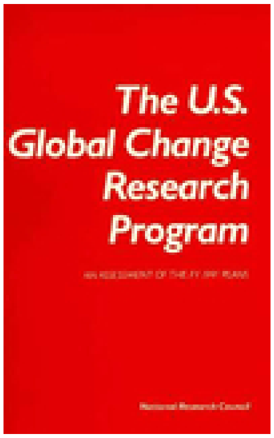

The U.S. Global Change Research Program: An Assessment of the FY 1991 Plans

Committee on Global Change, National Research Council

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The U.S. Global Change Research Program: An Assessment of FY 1991 Plans

National Research Council

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NATIONAL RESEARCH COUNCIL

2101 CONSTITUTION AVENUE WASHINGTON, D. C. 20418

OFFICE OF THE CHAIRMAN

The Honorable D. Allan Bromley
Assistant to the President
for Science and Technology
The White House
Washington, D.C. 20506

Dear Dr. Bromley:

On behalf of the National Research Council, we are pleased to transmit the accompanying report, *The U.S. Global Change Research Program: An Assessment of FY 1991 Plans*, as requested in your letter of January 29, 1990. The report was prepared by two panels organized under the auspices of our Committee on Global Change. The panels are to be commended for undertaking this study of a difficult issue where there are many points of view.

At the outset we recognized that the panels faced a complex and difficult task in reviewing such large programs under very tight time constraints. However, we felt that the NRC could usefully respond to the specific and focused questions posed in your letter. In our view, the panels have succeeded in the task set before them by scrutinizing the programs carefully, exposing both strong and weak points, and setting recommendations for future actions. At the same time, we want to note that the time constraints did not allow the panels to fully address all aspects and implications of the questions proposed.

The complexity of the Global Change Research Program and its interdisciplinary character make formulation of a comprehensive plan extremely difficult. The panels found that the research priorities outlined in the FY 1991 plan are consistent with the overall objective of achieving an improved understanding of global environmental processes. The panels have outlined a number of issues which we believe require early attention by the government if the program is to achieve many of its objectives. We highlight some of these below; others are elaborated in the text.

The report recommends that the agencies participating in the USGCRP develop a comprehensive global observational strategy for the program. The strategy would take into account complementary methods, whether space-based, airborne, or from the surface, as well as on-going observational systems operated on land, sea, and in space by agencies of the U.S. and other governments. The report does not address the question of the appropriate combination of space based, surface-based, or airborne research and monitoring activities that would be most cost-effective. To do so would have required considerably more information and time than were available for the study and would have required the development of a total program design, a task the panels were not requested to undertake. Nevertheless, this question deserves the attention of government managers.

The report concludes, however, that continuous, long-term, space-based observations of fundamental environmental parameters are essential for achieving the underlying goals of the USGCRP. The panels found that NASA's Earth Observing System, in conjunction with complementary space missions, will provide data central to many of the high-priority objectives of the USGCRP, if plans and schedules are met. Regarding the implementation of EOS, the report concludes that a significant measure of simultaneity is desirable for a number of instruments proposed to meet the research objectives of the EOS-A satellite series but has not been demonstrated to be necessary for the research objectives of the EOS-B series.

The report also concludes that if funding becomes a problem, spreading budget reductions evenly over all elements of the program would be damaging. Funding priority should be placed on projects of highest scientific priority. For the space components of the global observations system, the report concludes that it would be better to delay the launch of EOS spacecraft than to forego or diminish the effectiveness of precursor missions that are also intended to gather data essential to the USGCRP.

EOS is an extremely complex and costly undertaking and every step necessary to minimize risk of failure must be emphasized. A failure could result in many years of delay in obtaining essential environmental information. The report calls attention to the need for a more detailed contingency plan than currently exists. Such a contingency plan is essential to ensure continuity of observations, one of the central needs of the program. While most of the instruments proposed for EOS have had a history of technical development, the program envisions significant advances in remote-sensing technologies with attendant technical uncertainties. The risks range from the failure of individual instruments to a single-point system failure. It is not possible to assess the levels of such risks, but it is vital that contingencies be provided for.

D. Allan Bromley
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Finally, the report notes that the preeminent challenge to global change research is the synthesis of diverse data from many different sources. Investing in the early development of the EOS Data and Information System (EOSDIS) is necessary for the long-term success of the USGCRP. The intended scope of EOSDIS far exceeds that of any civilian data management system. The report concludes that a program of research and prototyping is needed to guide the evolution of EOSDIS.

The National Research Council is pleased to have had the opportunity to contribute in this way to the advancement of global change research.

Sincerely,

Frank Press
Chairman

Robert M. White
Vice-Chairman

PANEL TO REVIEW THE FY 1991 U.S. GLOBAL CHANGE RESEARCH PROGRAM

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PREFACE

On January 29, 1990, the Assistant to the President for Science and Technology, D. Allan Bromley, wrote to the Chairman of the National Research Council (NRC), Frank Press, asking the NRC to review the interagency U.S. Global Change Research Program (USGCRP), as described in the President's FY 1991 budget, and to address several specific questions about NASA's Earth Observing System (EOS) in that context. This report responds to that request.

The report was prepared under the auspices of the NRC's Committee on Global Change (CGC). Over the past seven years, the CGC and its predecessor committees have issued a series of reports advising government and the scientific community on the critical scientific questions about global change and the research strategies needed to address them. To conduct the current study, the CGC organized two panels, which worked concurrently. One panel reviewed the USGCRP while the other addressed the questions about EOS. To assure coordination and consistency in the panels' work, several people, including their respective chairs, served as members of both. Both panels were subject to the policy and procedures of the NRC regarding potential sources of bias and conflicts of interest.

The report is the work of the two panels. Part I was prepared by the Panel to Review the FY 1991 U.S. Global Change Research Program and Part II was prepared by the Panel to Review NASA's Earth Observing System in the Context of Global Change Research.

In conducting their assessments, the panels examined the summary budget analysis entitled *Our Changing Planet: The FY 1991 U. S. Global*

Change Research Program, a number of published reports on global change research and on EOS and related space-based observing missions, a forthcoming report on EOS being prepared by the NRC's Space Studies Board, and internal governmental working documents, some of which were only available in draft. In the limited time available for the study, each panel conducted two meetings at which it received briefings from agency personnel and contractors. In addition, the panels solicited the views of a number of colleagues to gain as broad a perspective as possible.

At the request of Dr. Bromley, the panels issued a preliminary report on March 30, 1990. The final report in hand here is consistent with the findings, conclusions, and recommendations of the preliminary report; it expands on the earlier analysis and extends it.

HAROLD A. MOONEY
CHAIRMAN
COMMITTEE ON GLOBAL CHANGE

The U.S. Global Change Research Program: An Assessment of FY 1991 Plans

SUMMARY

This report was prepared in response to a request that the National Research Council (NRC) assess whether the FY 1991 plan for the U.S. Global Change Research Program (USGCRP) is a sound approach to reducing the scientific uncertainties regarding global change issues. The charge included several specific questions concerning the plans for the Earth Observing System—a large, single initiative of NASA—in the context of the USGCRP. The report was prepared by two coordinated panels established under the auspices of the NRC Committee on Global Change.

ASSESSMENT OF THE FY 1991 USGCRP

The findings of the Panel to Review the FY 1991 U.S. Global Change Research Program are summarized as follows.

The interagency USGCRP, as described in the President's FY 1991 budget, defines an appropriate first step toward a sound national program to reduce the scientific uncertainties associated with global change issues. The program is clearly aimed at advancing our understanding of the Earth system. The FY 1991 plan reflects the priorities established by the scientific community over the past decade, primarily through the NRC, and an unprecedented level of interagency coordination realized through the Committee on Earth and Environmental Sciences (CEES). The plan is also coincident with the goals and activities of the international community, through organized projects of the International Geosphere-Biosphere Program and the World Climate Research Program.

The panel gave particular attention to the question of whether the FY 1991 program reflects appropriate balances in allocating resources. A specific issue was whether an appropriate balance was struck between initial investments in long-lead time, space-based efforts and investments in more immediate research endeavors. It is the view of the panel that the initial investments, though heavy, are both prudent and unavoidable, given that continuous, long-term, space-based observations of fundamental environmental parameters are essential to achieving the underlying goals of the program. Space-based observations will continue to require significant funding, but appropriate balance will also entail substantial growth in funding for other aspects of the program in the future to ensure that data acquired from space are used fully and that the broader program objectives are met.

The program also acknowledges other, equally important long-term investments for which long-lead planning is required. Most important among these are investments in education to build the cadre of scientists and technicians needed to carry out the program, and investments in fundamental research to increase the body of knowledge on which reliable projections of future change must be based.

Other elements of program balance considered by the panel included the balances between extra-mural and agency-based research; between "big" and "little" science; between established and emerging programs; and among observations, process studies, and modeling elements of the program; and among the seven science priorities identified in the plans for the USGCRP. We also examined the processes for coordination and review of the program, the involvement of the scientific community in program planning and review, mechanisms for scientific assessment and the delivery of policy advice, interactions among participating agencies, the need for international collaboration, the availability of human resources needed to meet program goals, and the status of "contributing" programs. We reached a number of conclusions and recommendations as summarized below.

- While the USGCRP includes observations, process studies and modeling, the FY 1991 program emphasizes observational programs because of the initiation of the Earth Observing System and Earth Probes series and the expense of space-based observing systems. The heavy emphasis on observations, necessary to initiate long-lead time, space-based capability, should be balanced as the program develops in the future by increased emphasis on process studies and modeling.
- The program would benefit from a better definition of the required national Earth system modeling capability and a workable plan for interpreting and delivering the results in forms useful to policymakers. These

omissions should be addressed soon if the program is to meet its announced objectives.

- The USGCRP is organized around seven scientific priorities. We conclude that the ranking of science priorities is consistent with the goals of the program and the consensus of the scientific community involved in global change research. The program would be strengthened if the science element focused on the study of how human activities influence and are influenced by global change ("human interactions") were better defined and more adequately funded. Priorities within the USGCRP must be kept flexible so that the program can remain responsive to research findings and unanticipated needs.
- The collaboration among agencies involved in the USGCRP has thus far been exemplary regarding definition and planning at the program level. The CEES has been an effective mechanism for this collaboration. The next challenge is to extend the collaborative approach to the specific activities or projects at the level of the Task Groups that now define activities within the science elements of the program. An ideal would be a "zero-based" project definition within each science element to discourage the re-labeling of prior agency initiatives only peripherally related to the goals of the program.

  A key example of where interagency collaboration is required is the development of an overall observational strategy, including space-based and in situ measurements, to monitor global change and collect data pertinent to process studies and modeling activities.
- USGCRP planning documents distinguish between "focused" (i.e., central) and "contributing" (i.e., supportive) programs. The focused elements do not represent the entirety of the required research, and many contributing programs and complementary activities in the President's budget must also be sustained if the program is to succeed. These contributing programs should be identified in a consistent manner.
- International collaboration on global change is required both to secure data on a global scale and to share human and financial resources. Cooperation with developing countries in global change research should be strengthened to ensure their involvement. U.S. support for international efforts, including an appropriate share of the support of program and project offices, should be made an explicit element of annual budgets.
- The role of the scientific community outside the participating agencies in providing for independent scientific review of the overall program should be more clearly defined, including the role of the NRC, and mechanisms for carrying out the reviews should be established.
- The USGCRP must strengthen the involvement and support of the academic research community, preferably through explicit programs

of extramural support in each of the agencies, to meet the long-term need for new scientists and technicians in the program and to ensure the participation of an adequate base of research scientists.

- Agencies with programs in the "focused" category (e.g., those programs included in the budget whose goals are regarded by CEES as central to the USGCRP) should be guided by extramural advisory panels to ensure appropriate focus and flexibility.

THE EARTH OBSERVING SYSTEM IN THE CONTEXT OF THE USGCRP

The findings of the Panel to Review NASA's Earth Observing System in the Context of the USGCRP are summarized as follows.

NASA's Earth Observing System (EOS) is intended as a major step in the evolution of the science and technology of global remote sensing. Its objective is to provide the user community (science, industry, policy) with the first comprehensive long-term measurement and data system specifically aimed at global change issues. EOS will also serve as a test bed for development of the next generation of operational Earth-observing instruments. The EOS Data and Information System (EOSDIS) is intended to provide means by which the scientific community can gain access to data obtained from EOS and elsewhere for use in documenting, monitoring, and modeling global environmental change and the Earth system.

Currently, EOS is at the point in the NASA process where instruments have been selected for development, but not yet selected for flight. Thus the information we had for this review was a "snapshot" in time of an ongoing process of development. All details of the mission have not yet been established, and even some of the major decisions have not yet been made. Mindful of this situation, we dealt with the information as part of a changing process, so that what we have provided here is an assessment that should itself be viewed as a snapshot of a developing program.

Our charge specified four questions, which are addressed in Chapters 5 through 8, respectively. We reached the following conclusions and recommendations.

- The set of instruments proposed and under consideration for flight would provide measurements of a number of high priority environmental parameters in the USGCRP framework. The complete set of measurements to be made from EOS spacecraft will depend on success in the development of the selected instruments and on other factors. EOS will not, however, provide all the space-based measurements required for understanding global change. Indeed, some parameters must be measured by space-based instruments on other satellites and in other orbits. Therefore, EOS must be viewed in the context of other space-based measurement systems of both the United States and other nations participating in global change research that will fly either before or during the proposed EOS measurement period.

- Documenting global change will require both space-based and in situ measurement programs, i.e., in the atmosphere, on the surface of the Earth, and on and in the oceans. The two types of measurements complement each other and a combination is essential; neither on its own is sufficient for the purposes of the USGCRP. There is as yet no comprehensive observational strategy that relates the total U.S. space-based observing program to the in situ measurements required for a comprehensive USGCRP, or that relates the U.S. measurement program to international efforts, both space-based and in situ. Such a multifaceted strategy is essential, and the agencies involved in the USGCRP should develop it soon based on work done to date. The strategy should allow for the evolution of observational goals and technologies.
- Certain sets of data should be collected simultaneously, depending primarily on the importance of studying the interactions within natural processes occurring over short time scales, and on the interdependence of certain sets of measurements for precise quantitative interpretation. The panel reviewed the arguments for simultaneity as applied to measurements aimed at studying the role of clouds in the climate and the hydrologic cycle and the fluxes of trace gases in biogeochemical cycles. We concluded that for measurements critical to these two high priority areas of research in the USGCRP, there is a need for several sets of instruments to make simultaneous measurements. These arguments lead to a set of overlapping requirements for a suite of instruments that should be flown on the same satellite. We are not aware of similar arguments for the measurements needed to address other scientific objectives of the USGCRP, such as those directed at the chemistry of the atmosphere and the dynamics of its upper reaches. While simultaneous measurement by individual pairs of instruments may be indicated for other scientific objectives, neither the scientific investigations nor the measurements themselves appear to demand the breadth of simultaneity essential to the study of the role of clouds in the climate and the biogeochemical dynamics of trace gases.
- For the two high priority areas described above, we concluded that the number of instruments that must fly together requires at least one large satellite. Dividing the proposed instruments for these measurements among several smaller satellites and flying them in close formation is technically feasible, but even the smallest coherent set of instruments for one of the small satellites is still sufficiently large to require a launch vehicle larger than the Delta rocket.
- The scientific requirements for continuity in data sets have led the community of researchers and NASA to plan for a long time-series

of measurements. EOS plans call for a 15-year record of observations using series of identical satellites, each with a 5-year lifetime, for each set of measurements. Measurements to carry out the USGCRP emphasis on the role of clouds and the fluxes of trace gases, for example, are planned for a series of large spacecraft called the EOS-A series. It seems likely that scientific understanding and technical capabilities will change during the course of the EOS program. Accordingly, although continuity of specific data sets will be an important consideration, it may also be desirable to alter the instruments or the platforms, or both, at some time in the future. NASA is designing the spacecraft and instruments to have common interfaces, which should make future interchange of instruments easier than on past missions. Currently, however, the program contains no process that would enable it to evolve in response to new scientific understanding, concepts, or technology as they emerge during the life of the EOS program.

- Scientific arguments for simultaneity in terms of the other research objectives of the second proposed satellite series, EOS-B, have not been developed by NASA; it currently appears that these objectives could also be achieved with a number of smaller, independent satellites. NASA's current assessment of comparative costs, as presented to us, suggests that flying the projected EOS-B instruments on large spacecraft is the least expensive option, although the differences in cost among some alternative configurations appear to be relatively small. In principle, the science investigations proposed for EOS-B could be done by a suite of smaller satellites. Since a number of the instruments do not require extensive development, these could perhaps be launched sooner.
- The first EOS satellite is scheduled to be launched in 1998. In the interim, significant opportunities exist for gathering key global change data through a number of U.S. and foreign research and operational satellite missions. Such missions include Upper Atmosphere Research Satellite, The Ocean Topography Experiment/Poseidon, and some of the Earth Probes. However, we note a gap in the critical area of Earth radiation budget measurements. It is intended that some of the EOS instruments should continue to monitor certain environmental parameters so that the precursor missions flying similar instruments will be prerequisites, not substitutes. We believe that, if budget constraints arise, it would be more desirable to delay the launch of EOS spacecraft than to forego or diminish the effectiveness of the near-term missions.
- The continuity and reliability of data used to monitor global change as it occurs are particularly important. NASA needs a more thorough contingency plan in the event of failures. When the potential for long-term drift in instruments is considered, it is clear that the issue of calibration warrants continuing attention.

- The preeminent challenge to global change research is the synthesis of diverse types of information from many different sources. The EOS Data and Information System (EOSDIS) will be a pioneering effort in this regard; the intended scope of the system far exceeds that of any existing civilian data management system.
- Investing in the early development of EOSDIS is appropriate and necessary for the long-term success of the EOS data collection, management, and modeling effort as well as for the USGCRP. Investment, however, does not guarantee success. While relevant experience for developing EOSDIS exists, no operational paradigm for the management and dissemination of such large scientific datasets currently exists.
- EOSDIS is planned as an must be an evolving entity. NASA should not attempt to define the total system specifications of EOSDIS at the outset and then assume that they will not be altered throughout the remainder of the program.
- EOSDIS should include and accommodate more than just data from EOS sensors in order to meet the needs of the USGCRP. The agencies prominent in the collection and dissemination of data—NASA, NOAA, NSF, and USGS—have a special responsibility to continue to work together and with the international community to assure that all relevant data and information are available to EOSDIS for global change research.
- The management of very large databases with provisions for indexing, browsing, visualization, and other capabilities should be viewed as a research issue. Current understanding of how to meet the challenge is not mature. A program of research and prototyping is needed to guide the evolution of the proposed data management capabilities.
- We welcome NASA's policies regarding access to EOSDIS data and data products, which are aimed at making them equally available to all users and to researchers at nominal costs of reproduction and delivery. Means should be found to include commercialized Landsat data in EOSDIS.
- Because the implementation of EOSDIS poses significant, continuing challenges, EOSDIS should have an ongoing mechanism for acquiring independent advice from the user community. The EOS Investigators' Science Advisory Panel for EOSDIS has successfully focused the concerns of a broader research community, and the panel should continue to be a long-term advisory element in the planning and implementation of EOSDIS. The panel should include some scientists who are not EOS investigators, but who are active in fields within the range of scientific disciplines involved in global change research, as well as in research on data and information management.

PART I:

THE U.S. GLOBAL CHANGE RESEARCH PROGRAM REPORT OF THE PANEL TO REVIEW THE FY 1991 U.S. GLOBAL CHANGE RESEARCH PROGRAM

Introduction

The U.S. Global Change Research Program (USGCRP) is an initiative of the U.S. government aimed at establishing the scientific basis for national and international policymaking relating to natural and human-induced changes in the global earth system. As such, the program calls for broadly-based research and modeling efforts within academia, government laboratories, and other research centers as well as observational systems to supply information on the earth system. The program is broadly constituted to include the study of the various dynamic and interrelated components of the earth system, including the human influences affecting and affected by global environmental changes. Currently, seven science elements constitute the framework for the program, each including focused research, modeling, and observational activities. The seven elements are: physical climate and hydrological systems, biogeochemical dynamics, ecological systems, Earth system history, human interactions, solid Earth processes and solar influences. The Earth Observing System, discussed in Part II of this report, is one major NASA initiative within the USGCRP.

The USGCRP, formally initiated in FY 1990, is formulated by the interagency Committee on Earth and Environmental Sciences (CEES)[1] under the Office of Science and Technology Policy's Federal Coordinating Council for Science, Engineering, and Technology. Within the CEES, the Working Group on Global Change, composed of representatives of seven participating agencies, develops plans for the program and coordinates these plans among the agencies. Separate working groups concerning research on mitigation and adaptation to global change and on groundwater are working in parallel to the working group on global change under the CEES.

[1] The CEES was known as the Committee on Earth Sciences until the spring of 1990.

The formal initiation of the USGCRP was the result of an evolutionary process within the scientific community and the federal agencies over the last decade. In 1983, the National Research Council (NRC) organized a workshop on the International Geosphere-Biosphere Program (IGBP) to consider the major questions for research on the atmosphere, oceans, lithosphere, biosphere, and solar-terrestrial interactions. The workshop concluded that a unifying theme for these research areas is the concept of global change. Subsequently, NRC issued a report in 1986, *Global Change in the Geosphere-Biosphere: Initial Priorities for an IGBP*, defining a conceptual approach for the study of the interacting components of the earth system. This approach is reflected in the IGBP, formally initiated by the International Council of Scientific Unions in 1986, of which the USGCRP is a major national contributing program. The NRC has since developed a number of scientific priorities for the study of global change, as reflected in the 1988 reports *Toward an Understanding of Global Change: Initial Priorities for U.S. Contributions to the IGBP* and *The Twenty-First Century: Mission to Planet Earth*, and the forthcoming report on *Research Strategies for the U.S. Global Change Research Program*. Within NASA, the report from a 1982 workshop, *Global Change: Impacts on Habitability: A Scientific Basis for Assessment* and subsequent reports, most notably the 1988 report *Earth System Science: A Program for Global Change*, similarly helped to develop consensus within the scientific community on the needs for national and international research programs to understand global change. These reports collectively provide a rigorous assessment of the state of science and gaps in knowledge needed to improve understanding of natural and anthropogenic changes in the global environment, and they form the basis for assessing the federal research plan.

The Panel to Review the FY 1991 USGCRP based its assessment on the brief description of the FY 1991 plans contained in the January 1990 document *Our Changing Planet* and brief one page descriptions of the projects included within each of the science elements for the FY 1991 budget. Because of the lack of detail in these documents, the panel consciously concentrated on general concerns about the USGCRP, rather than on specific analysis of the projects and plans for FY 1991. The panel formulated four questions for assessment: Does the program address the scientific priorities for reducing uncertainties about global environmental change? Is the USGCRP an appropriately balanced program? Are current processes of coordination and review adequate? And what other issues require particular attention in the implementation of the program? The four questions are addressed in Chapters 1 through 4 respectively. Appendix B is a commentary on projects in the science priority elements of the USGCRP.

1

Reducing Uncertainties

Does the Program Address the Scientific Priorities for Reducing Uncertainties about Global Environmental Change?

Based on our review, we conclude that the interagency USGCRP, as described in the President's FY 1991 budget, defines an appropriate first step toward a sound national program to reduce the scientific uncertainties associated with global change issues. The program is clearly aimed at advancing our understanding of the earth system. If successfully pursued it should improve our ability to identify trends and anticipate effects of many of the environmental changes that are currently perceived as likely to be of greatest consequence over the next 10 to 100 years.

The focus of the program—with greatest initial emphasis given, in order of priority, to climate and hydrologic systems, biogeochemistry, ecological systems, earth system history, and the human dimensions of global change with somewhat lesser emphasis on solid earth processes and solar influences—is in our view appropriate to achieve its stated goals. In making a heavy initial investment in a space-based observational system, the program lays the foundation for obtaining sustained, long-term measurements of certain of the vital signs of the earth; it also initiates a modern data and information system (EOSDIS) that will make the data readily available to those who need them.

Scientific priorities for reducing uncertainties about global change have been developed by the NRC and other bodies in a series of studies over the past seven years. Documents of those efforts include the report of the NASA Earth System Science Committee (*Earth System Science: A Program for Global Change, 1988*); reports of the National Research Council that have recommended and defined a global change program (*Global Change in the Geosphere-Biosphere, 1986; Toward an Understanding of Global Change, 1988*); a Space Science Board report (*The Twenty-First Century: Mission to Planet Earth, 1988*); and international planning documents for the International Geosphere-Biosphere Program and World Climate Research Program. These documents underscore that if changes in the global environment are to be understood and predicted, knowledge of how the earth works as a system must be expanded, with particular emphasis on the connections that link climate, biogeochemistry, ecological systems, human aspects of change, and the development of earth system models that will allow improved predictions. The reports also recommend that certain priority parameters of the earth system be under extensive, long-term surveillance, and that the results of monitoring be made freely available both nationally and internationally. The USGCRP has been designed by the CEES to follow these guidelines, and it is clearly coincident with the recommendations from the scientific community.

While the scientific priorities identified in the FY 1991 plan seem appropriate, given current knowledge, it is necessary that the plans be kept flexible and are under continual review as the program evolves. The USGCRP does now and must continue to address issues broader than climate and deeper than the sometimes ephemeral concerns that readily attract public attention. The broader issues potentially include changes in the chemistry and quality of not only the atmosphere but also the soils and surface and subsurface waters and the oceans themselves; reductions in biodiversity from deforestation and other land use practices; and other responses of the earth system to extensive agriculture, industry, urbanization, land use alterations, the spread of anthropogenic pollutants, and other changes induced by humans. Some of these problems are addressed by the FY 1991 plan; others, such as reductions in biodiversity and the human causes and responses to change (e.g., impacts on agricultural systems and public health) are addressed inadequately or not at all.

Today public and policy concern is riveted on anticipated greenhouse warming, with added concern regarding the depletion of stratospheric ozone, acid precipitation, and tropical deforestation. Continued stress on the environment, driven by a burgeoning world population, will expose new and perhaps unexpected concerns that may prove as significant—if not more so—than any of these. The usefulness of the USGCRP will rest ultimately on its ability to shift focus, as needed, to apply the energies of an organized research community to new and unanticipated concerns about the global environment, and to distinguish long-term significant issues from those that are ephemeral. The program can best achieve this by holding to its original goal of understanding the earth as a system—including the role of humans as well as the natural variability of the system—and by documenting significant trends in global change, without any prescience of what these changes will be or any prejudice as to where or how they will emerge. The program must therefore be ready to add or drop priorities as scientific insights develop. It must also exert particular prudence in the selection of instruments and parameters that are to be monitored from space, where costs and long lead times have the most limiting effects.

PRINCIPAL RECOMMENDATIONS

The panel endorses the general scientific priorities of the USGCRP and urges that they be kept flexible in ensuing years. To maintain the required program flexibility and to ensure its appropriate direction, we urge that the USGCRP be reviewed at frequent intervals by scientists who are sufficiently detached from the agencies that implement the program to render impartial judgements.

2

Appropriate Balance

Does the USGCRP Strike an Appropriate Balance?

A particular question, often asked, was whether the FY 1991 program reflects an appropriate balance between initial investments in long-lead time, space-based efforts (specifically the new research initiatives of the Earth Observing System and the Earth Probes series of smaller spacecraft) and investments in more immediate and often less expensive research needs.

In considering this particular and other more general questions we need first to define "appropriate balance" (one in which resources are allocated to program components in a manner that will best achieve overall program goals) and then, using this standard, to weigh the program in several ways. Six ways of evaluating balance are discussed below, followed by a set of overall conclusions.

BALANCE BETWEEN LONG-TERM AND SHORT-TERM INVESTMENTS

The USGCRP, envirsaged as an effort that will span several decades, requires early investment in a number of essential program elements that by their nature require long-lead times. These long-term efforts must be balanced against those that can be immediately set in motion and that may yield results over a shorter term.

The most obvious of the long-lead items involve spacecraft, and it is in this area that the FY 1991 program puts much of its budget. It is the view of the panel that this is both prudent and unavoidable, given that continuous, long-term, space-based measurements of fundamental earth parameters are essential to achieving the underlying goals of the USGCRP. Space-based instruments and operations are of necessity expensive. Thus it should be expected that the USGCRP must invest substantially, early in the program, in long-lead, space-based capabilities. Part II of this report examines more specific issues regarding the EOS and Earth Probe systems.

To realize the potential of this investment, it is necessary that it be balanced by an appropriate investment in the broader needs of the program, including human resources and the infrastructure of basic research that is needed to use the data that will be acquired from space. It is the opinion of the panel that this will require, in future years, a heavier commitment to shorter-term investments and to long-term non-space-based efforts than the committment included in the FY 1991 plan.

Examples of research activities carrying the promise of shorter term payoffs that should be strengthened and supported include some currently planned space missions such as TOPEX, existing programs that will contribute to the USGCRP, efforts in data collection and assimilation, and current efforts to model the earth system.

Included in the long-lead, long-term investments that do not involve space are investments in education, to establish a pool of human resources adequate to address both the scientific and technical aspects of global change issues, and a strengthening of basic research into the processes involved in global change, in both disciplinary and interdisciplinary areas. Both of these long-lead elements can only be addressed with full involvement of the academic community.

BALANCE BETWEEN EXTRAMURAL AND AGENCY-BASED RESEARCH

All the scientists who were consulted in the process of the panel's review expressed strong support for the USGCRP. Many, however, were concerned that the USGCRP—defined as it is by the CEES through agency initiatives—might appropriate the more critical elements of the program to create intramural endeavors, or to fund existing initiatives in the name of USGCRP. If in-house, agency research endeavors were allowed to dominate, the program would almost certainly lose the active support and involvement of those academic scientists who have provided the ideas on which the program is based and whose contributions have traditionally defined the cutting edge of research.

There are several reasons why the strengths of the academic community need to be more be fully used in the USGCRP. Most importantly, the USGCRP will require trained scientists in emerging areas of program focus, in most cases more scientists than currently exist. The needed recruitment and education can best be carried out within a university community that is involved in global change research and adequately supported to carry it out, and when students perceive that there is a national commitment to continued global change research. Other elements of the research community—federal laboratories, centers, and industry—complement the universities by providing supplemental training, but they are not well suited to educating large numbers of advanced students. Researchers in the academic community will also make strong intellectual contributions in many of the scientific fields that must grow and adapt to new problems of global change.

The materials available to the panel were not adequate to allow an assessment of the balance in funding in the FY 1991 program between in-house, agency initiatives and funding for extramural research. The concerns outlined above could be alleviated, however, were each agency involved in the USGCRP to establish an extramural research program coordinated with its in-house research endeavors. In addition, it would facilitate program review if each agency were to provide a breakdown of its entire USGCRP program contribution showing proposed distribution between extramural and in-house efforts. What constitutes an "appropriate balance" will obviously differ among agencies because of their different missions. The panel recommends that the two steps just described be adopted in the development of future budgets for the program.

BALANCE BETWEEN "BIG" AND "LITTLE" SCIENCE

The needs of global change research require that a balance be maintained between large organized projects and research carried out by individuals or team investigators. By definition, much research in the science of global change requires global data sets and large-scale analyses, involving coordination and instruments that are obtainable only through organized national and international programs of research. At the same time, much of the "little" science that is carried out today by investigators or teams is made possible by data acquired through "big science" efforts, such as the World Climate Research Program. Needed is an appropriate balance of the two.

Innovative research by individual investigators has traditionally defined the forefront of scientific discovery, and it is clearly requisite to the success of the USGCRP. This capability can best be advanced by (1) identifying within each science priority element adequate extramural funding for research, as recommended above; (2) involving the extramural community in programmatic review at a variety of levels (both agency and cross-agency); (3) maintaining sufficient flexibility in the program to make possible the support of innovative individual research; and (4) maintaining a program focus that is intellectually challenging so as to attract the most able scientists, whether they work independently or through organized activities.

In the opinion of the panel, the FY 1991 USGCRP plans would be strengthened if areas (1) and (2) above were more clearly supported.

BALANCE AMONG OBSERVATIONS, PROCESS STUDIES, AND MODELING

The USGCRP comprises three fundamental elements: observations to provide global, long-term data sets for detecting change, focused studies to improve understanding of fundamental earth system processes, and analytical modeling to develop the ability to predict future changes. The three are interactive and interdependent and must be developed in parallel. Process studies to improve understanding of global change and observational activities often proceed interactively. The results from the process studies and observations furnish information for model building, and the results of the models results often stimulate new process studies and observations.

As noted earlier, investment in observational systems dominates the proposed budget for reasons that seem necessary to the panel. The mission of the program requires a combination of space-and ground-based observations to provide global, long-term data sets for detecting change. Although the EOS and Earth Probes include support for associated, ground-based activities, they clearly do not address all program needs for in situ data. Many of the data sets for the USGCRP will have to be secured on or near the surface. It will be necessary that the program include needs for in situ data and the complementarity of space-based and in situ observational programs more explicitly than in the FY 1991 program.

In succeeding years of the USGCRP, the two other fundamental elements of the program—process studies and modeling—must be emphasized more strongly. Process studies constitute the intellectual driving force of the program. The support for research dealing with process studies, particularly studies that address issues that cut across the seven USGCRP science elements, needs to be strengthened in future years.

Although acknowledged in earlier USGCRP documents as the ultimate goal of the program, support for the conceptual efforts needed in modeling is notably lacking in the FY 1991 plan. Two gaps now exist in the modeling aspects of the program: (1) a specification of what the program requires in the way of a national earth system modeling capability, including but extending beyond improved climate system modeling, with an interagency plan that will support it; and (2) a workable plan for interpreting and delivering the results in a form useful to policymakers. It is not too soon to focus on requirements for the first of these given the lead times required to build multi-disciplinary groups of modelers and any new institutions that may be required. How these central issues will be met will need to be addressed in future descriptions of the USGCRP, through a comprehensive national plan, including the role of EOSDIS in modeling efforts.

BALANCE BETWEEN ESTABLISHED AND EMERGING PROGRAMS

The research needed to address issues of global change, as defined nationally by the NRC and the CEES and internationally by ICSU and the WMO, rests on the foundation of a number of contributing programs of research that are already in motion. Among these are the program on International Global Atmospheric Chemistry (IGAC), the Joint Global Ocean Flux Study (JGOFS), and elements of the World Climate Research Program (WCRP), including the World Ocean Circulation Experiment (WOCE), Tropical Ocean-Global Atmosphere (TOGA), and the Global Energy and Water Experiment (GEWEX). Plans for these programs have been developed over a number of years and represent the consensus of the scientific community involved in global change. Given the current atmosphere of interest in global change, however, it is a great deal easier to invent new programs than to support them once they are established. There is a concern that these necessary, existing programs will suffer as new projects are defined.

It would be counterproductive if new elements of the USGCRP were to be initiated at the expense of the established programs on which progress of the overall program depends. A related hazard, given the array of new and existing program elements, is that of underfunding, in the sense of support below the level needed to sustain progress. As cuts are weighed in the overall USGCRP budget in any year, reductions will need to be considered in light of the highest priority needs of the program as a whole. It would be damaging, in the view of the panel, if a potential need to reduce budgets were to be spread evenly over all elements of the program.

This element of balance can be addressed directly if the support for contributing programs is made an explicit element of future budgets for the USGCRP.

BALANCE AMONG SCIENCE PRIORITIES

The USGCRP identifies seven science priorities, gives them relative rank, and further identifies priority tasks within each of them. The panel concludes that the priorities are generally consistent with the goals and initial aims of the program and with the recommendations of the CGC. A further measure is how well the funding proposed in the FY 1991 budget conforms to the adopted priorities. In Appendix B, we briefly assess how each of the CEES science priorities and the underlying needs of Modeling, Data and Information Systems, and Documenting Change are treated in the FY 1991 budget.

As noted in Appendix B, the panel finds both the program definition and the level of support for the USGCRP science element concerning "human interactions" notably deficient when balanced with the other elements of the program.

PRINCIPAL RECOMMENDATIONS

The panel recommends that, in preparing future versions of the plan, CEES explicitly consider the above six dimensions of scientific balance for the program as discussed in this chapter, and that these dimensions be employed as explicit criteria in program evaluation. The involvement of the extramural scientific community in the process through advisory and review mechanisms seems essential to this purpose.

3

Processes for Coordination and Review

Are Current Processes of Coordination and Review Adequate?

A particular strength of the USGCRP is the high degree of collaboration among the major research agencies that fund and carry out research in the biological and earth sciences, realized organizationally through the CEES. These efforts have developed a working, multi-agency process whereby plans for the USGCRP are coordinated through the CEES Working Group on Global Change and its various Task Groups. The process can focus joint resources on areas of research that are of broad national and international concern. The CEES planning process offers as well an additional mechanism to preserve program focus, through procedures of the CEES that now subject proposed USGCRP initiatives of individual agencies to interagency scrutiny.

The CEES interagency approach is a useful mechanism which, if effectively coupled with ongoing, external review processes, has the potential to provide the structure for an exceptionally strong program of research. Three particular needs are outlined below.

CONTINUED INVOLVEMENT OF THE SCIENTIFIC COMMUNITY IN PROGRAM PLANNING AND REVIEW

In the formative stages of the USGCRP, independent advice on the overall scientific strategy and approach of the program was provided through a close working relationship with the NRC's Committee on Global Change. As the USGCRP enters its implementation phase, the activities of the CGC and other advisory mechanisms will have to shift emphasis to include more directed activities of periodic program review and reevaluation.

The panel sees a need as well for extramural advisory panels to guide and review programs within each of the federal agencies that contribute to the focused program. Such panels can provide an effective mechanism for maintaining the elements of balance discussed above, to ensure program flexibility, and to preserve the needed program focus. Some but not all agencies with focused program elements now use panels of this sort.

MECHANISMS FOR SCIENTIFIC ASSESSMENT AND THE DELIVERY OF POLICY ADVICE

The USGCRP is designed to establish the scientific basis for national and international policymaking with the goal of providing an objective foundation of fact for rational policy debate and effective action. Specifically, the program promises to deliver (1) timely information to Congress, the Executive Branch, and others; (2) periodic assessments of scientific understanding in critical areas of global change; and (3) seasonal, interannual, and ultimately interdecadal projections of selected climate impacts.

The mechanisms that will be needed to achieve these goals, involving assimilation of results including those of modeling and processes of responsible review and consensus, are not specified in plans for the USGCRP, but they will soon need to be. Nor is it clear which agency, or agencies, will take the lead in performing these important roles. The degree to which reliable projections can realistically be expected, the specifications of well-reasoned limits on their accuracy and the process through which projections are to be provided and delivered are as yet undefined. The panel feels that filling this void must be a priority element of subsequent budgets for the program.

INTERACTION AMONG PARTICIPATING AGENCIES

The USGCRP has developed on the basis of extraordinary cooperation and interaction among many federal agencies through the CEES. Interagency agreement on program goals, the ordering of scientific priorities of research tasks within them, and agreements on an overall, multi-agency program budget reflect what may be an unprecedented achievement in interagency coordination.

While this exemplary level of coordination applies to the program as a whole, it is not as evident in the selection of agency initiatives that are proposed to achieve progress in the various science priorities. Lacking in some cases, in the view of the panel, is evidence of what might be called "zero-based" program definition, i.e., interagency agreement for each science priority on what is needed to answer the highest priority research questions, whether or not the needed initiatives now exist within a given agency. Several perceived shortcomings are noted in Appendix B. The need for increased interagency interaction at this level applies to most if not all of the identified science priorities.

Improved definitions can be achieved in future years through more specific program recommendations on the part of the CGC and through implementation of them on the part of interagency Task Groups that have now been established by the CEES.

PRINCIPAL RECOMMENDATIONS

The panel believes that the multi-agency process established through the CEES provides the mechanism for a coordinated, effective program. However, mechanisms need to be strengthened to involve the extramural scientific community in the review of the USGCRP plans, both at the levels of both the overall program and the individual participating agencies. In addition, mechanisms need to be developed for evaluating the successes of the program, for delivering results to policymakers, and for improving interaction among the participating agencies on specific projects included within the USGCRP.

4

Other Issues

What Other Issues Require Particular Attention in the Implementation of the Program?

INTERNATIONAL COLLABORATION IN GLOBAL CHANGE RESEARCH

The ability of the USGCRP to secure data that are available or must be acquired elsewhere in the world, to conduct the process research, to build the analytical models needed to meet its goals, and to meet the demands that the program will place on human and financial resources will require a truly international effort. The International Geosphere-Biosphere Program organized under the auspices of the International Council of Scientific Unions (ICSU) and the World Climate Research Program organized under ICSU and the World Meteorological Organization are the international counterparts of the USGCRP, and they share the same objectives as the USGCRP. Coordination between USGCRP activities and internationally-organized programs of research should be strengthened. Collaboration with other countries should be encouraged as well, on a bilateral or multinational basis. (See Chapter 5 for a discussion of the need for an internationally coordinated observational strategy.)

In many countries, national research activities that parallel those of the USGCRP are now under way. In others, research programs that deal with global change are currently very limited. It is obviously necessary for the success of the U.S. program that such national activities be encouraged and helped, where needed, either bilaterally or through sharing of international program expenses. In particular, we recommend that cooperation with developing countries in global change research be strengthened to ensure their involvement and that plans for doing so be developed by agencies involved in the program.

These international endeavors are not included as explicit elements of the FY 1991 program. The degree to which each element of the USGCRP contributes to or benefits from related international, multinational, or bilateral efforts should be made more explicit in future descriptions of program elements and in future budgets for the program. U.S. support for international efforts, including the appropriate share of this nation in support of program and project offices and necessary international travel of involved U.S. scientists are investments in the goals of the USGCRP and should be made an explicit element of annual budgets for the program.

AVAILABILITY OF HUMAN RESOURCES

The availability of sufficient human resources to carry out the program may well prove the most important determinant of the success or failure of the USGCRP. Plans for the USGCRP recognize the vital need to provide opportunities for recruiting and educating students who will become the next generation of research scientists and technicians needed to sustain the program. In many areas of science the USGCRP will require substantially larger research communities than those that currently exist. Examples are found in the fields of global ecology, hydrology, biogeochemistry, and in other areas of interaction that link conventional academic disciplines, and in the emerging area of human interactions. We can assume that increased, sustained levels of funding in these and other areas will attract an increasing number of scientists. Innovative programs to encourage specific careers in both disciplinary and interdisciplinary specialties will also be required. Increased attention will have to be paid to education and to the rates at which these communities can grow.

As noted above, a first step toward this end can be taken by entraining the academic research community in the program, through agency programs of extramural research support.

DEFINITION OF "CONTRIBUTING" PROGRAMS

The FY 1991 program plan and earlier documents of the CEES divide the USGCRP into "focused" (e.g., those programs whose goals are regarded by the CEES as central to the USGCRP) and "contributing" (e.g., those programs that CEES regards as supportive of the goals of the USGCRP but that were initiated for other reasons) elements. Funds for "focused" programs are included within the overall USGCRP budget, while funds for "contributing" projects are not.

The "focused" elements do not attempt to provide the entirety of the research that will be required to meet the aims and goals of the program. Vital "contributing" programs and additional complementary activities conducted through other federal programs—for example, the program of operational meteorological satellites within NOAA—must also be sustained if the program is to succeed. It follows that any critical review of the overall program must be guided by a more explicit identification of "contributing" programs, and a distinction between "focused" and "contributing" elements that is consistent across participating agencies.

PRINCIPAL RECOMMENDATIONS

The panel makes the following recommendations regarding three issues that should receive particular attention in future plans for the USGCRP: (1) international collaboration between programs within the USGCRP and programs within existing international research programs on global change should be strengthened and explicitly defined; in addition, bilateral and multilateral research endeavors on global change should be vigourously pursued, particularly with developing countries; (2) innovative plans to encourage careers in global change research should be undertaken to develop the human resources necessary to carry out the program; as a first step, support for academic research on global change is needed to attract students to choose careers in this area; and (3) "contributing" programs essential to the success of the USGCRP should be more clearly defined and distinctions between "focused" and "contributing" programs should be made consistent across the contributing agencies.

PART II:

THE CONTRIBUTIONS OF EOS REPORT OF THE PANEL TO REVIEW NASA'S EARTH OBSERVING SYSTEM IN THE CONTEXT OF THE USGCRP

Introduction

NASA's Earth Observing System (EOS) has been designed to build on 30 years of scientific and technical experience in remote sensing from space. As the technology has matured from the early weather satellites, the Earth science community has had the opportunity to integrate remote sensing techniques and data products into its research. The new data have answered many questions but raised more. The existence of global measurement techniques and modern computational capabilities has led to significant advances in the conceptual approach to the study of a natural environment—from a disciplinary to an interdisciplinary focus and from a local or regional to a global perspective. Over the past decade, these developments have contributed to the emergence of a new field of scientific inquiry, Earth system science, and to international research activities such as the World Climate Research Program (WCRP) and the International Geosphere-Biosphere Program (IGBP), and to the initiation of the U.S. Global Change Research Program (USGCRP). Satellite measurement programs are a key element of Earth system science.

In the EOS program, NASA proposes a major step in the evolution of the science and technology of global remote sensing and microwave imagers that provide detailed images of the Earth's surface; tropospheric and stratospheric sounders that provide vertical profiles of parameters such as temperature, trace gas concentration, and humidity; and accurate positioning instruments. EOS will carry two classes of instruments: facility and principal investigator (PI) instruments. The facility class instruments are those that NASA will supply in response to the general mission; the

PI class instruments were selected through a competition and are aimed at the specific focused research interests of the selected investigators.

The objective of EOS is to integrate a number of related, but previously unavailable or disparate, space-based measurements into one continuing system and thereby to enhance research capabilities significantly. It will also provide a test bed for the development of the next generation of operational, Earth-observing instruments and measurement techniques. EOS is designed to yield a long-term, continuous set of high-priority measurements on a global basis that are consistent with the needs of the U.S. Global Change Research Program (USGCRP). The measurements will be combined with complementary data obtained from space, suborbital, and surface-based sources into the EOS Data and Information System (EOSDIS). The comprehensive contents of EOSDIS are intended to enable the scientific community to document, monitor, and model environmental change, to broaden its understanding of the entire Earth system, and to improve predictive capabilities. Both the EOS space-based measurements and EOSDIS are planned as interdisciplinary, interagency, international endeavors, all of which are essential features of the USGCRP.

While EOS as proposed would provide extensive capabilities in remote sensing and data management, it is best understood in the larger context of NASA's Mission to Planet Earth and the even broader context of the programs and plans for remote sensing of other agencies and nations. The framework of the Mission to Planet Earth includes a number of near-term smaller satellite missions (Earth Probes) to provide essential data and added flexibility to the overall program. Both EOS and Earth Probes are included in the FY 1991 USGCRP. Geostationary platforms for continuous synoptic observations are being considered for later flight.

This report is based on a review of the most recent NASA documentation on the current status of the proposed EOS, including the 1990 EOS Reference Handbook (published by NASA), several briefing reports, and oral briefings. In particular, we, the panel, had access to the draft report of the Space Studies Board's Committee on Earth Studies (SSB/CES), which examines the EOS initiative in a broader context. That report will be issued after this one. We also received a copy of a review of EOS by the American Geophysical Union, draft letters on instrument selection and data simultaneity from the Chairman of the EOS Payload Advisory Panel to NASA's Associate Administrator for Space Science and Applications, and the latest information on plans for the USGCRP.

Currently EOS is at the point in the NASA process where instruments have been selected for development, but not yet selected for flight. Thus the information we had for this review was a "snapshot" in time of an ongoing process of development. All details of the mission have not yet been established, and even some of the major decisions have not yet been made. Mindful of this situation, we dealt with the information as part of a changing process, so that what we have provided here is an assessment that should itself be viewed as a snapshot of a developing program.

Because of the limited time available, we were not able to review many aspects of this complex program in detail. Moreover, as noted below, much of the documentation for the program is fragmentary and informal. In spite of this limitation, we believe that our general conclusions are sound. Because of the importance of this program to Earth scientists and to the U.S. Global Change Research Program in general, we recommend that a continuing overview by independent nongovernmental scientists and engineers be maintained.

We were charged to address four questions. They appear verbatim at the openings of Chapters 5 through 8 below and are followed in each case by our responses and recommendations.

5

Environmental Parameters

Does EOS collect the environmental parameters that are reflected in the USGCRP research priority framework and related policy issues described in "Our Changing Planet"?

To answer this question, we first considered the overall USGCRP research priority framework, which states three integrating priorities: (1) documentation of Earth system change with observational programs and data management systems; (2) improvement of understanding through focused studies of the controlling physical and biogeochemical processes; and (3) development of integrated conceptual and predictive models. EOS is designed to contribute primarily to items (1) and (2); EOS data will also be used in the development, validation, and ultimate applications in (3). The relative emphasis EOS places on process studies and monitoring global change is one that will evolve. At present, EOS is intended to contribute to both, with a stronger focus on process studies. In the long run, it will become a major system for monitoring global change. The changing nature of these roles must be recognized and flexibility must be built into the system so that EOS can adapt.

In summary, we find that EOS is being designed to measure environmental parameters from space that reflect the USGCRP framework and that will allow researchers to make major contributions to global change research. However, there are general strategy issues that need further development, and we have also identified some specific issues involving instruments.

THE MEASUREMENT SYSTEM FOR GLOBAL CHANGE

It is generally agreed throughout the international scientific community associated with global change that adequate documentation of environmental change on Earth requires a combination of space-based and in situ measurements. "In situ" in this sense means in the atmosphere, on the surface of the Earth, and on and in the oceans.

The need for this combination of space-and Earth-based measurements is well-documented in reports from the NRC and from NASA. The most recent NRC reports come from the Committee on Science, Engineering, and Public Policy (*Report of the Research Briefing Panel on Remote Sensing of the Earth*, 1985); from the Committee on Earth Sciences and the Task Group on Earth Sciences of the Space Studies Board (*A Strategy for Earth Science from Space in the 1980s and 1990s*, Parts I and II, 1982, 1985; *Mission to Planet Earth*, 1988). The most recent NASA report addressing the full set of science issues, with recommendations for both NASA and NOAA, comes from the Earth System Science Committee (*Earth System Science: A Closer View*, 1988). The NRC and NASA reports are the work of a representative and broad segment of the U.S. scientific community, and we believe that those reports accurately reflect broadly held views.

The two types of measurements complement each other. Space-based measurements can provide a global and synoptic view of Earth's environmental parameters and processes not available any other way. In situ measurements document those processes not accessible from space, such as deep ocean currents. Cloud cover prevents many important measurements from being made from space; for a number of process studies, observations are needed within and under clouds. Moreover, the vertical and horizontal resolution and accuracy of certain variables that can be obtained from space are inadequate for certain process studies of importance to global change. Thus there will always be a need for in situ measurements as part of a global change observing system. The combination of space-and Earth-based measurements is essential; neither can provide a complete picture on its own.

There are important variables, such as chemical constituents and other internal variables of the ocean, that cannot be measured at all from space; other variables, such as cloud droplet distribution and turbulence, cannot currently be measured well from space.

The requirement for complementary measurements has been met for several near-term satellite systems by the development of large coordinated in situ programs. For example, the World Ocean Circulation Experiment (WOCE) was designed to carry out global in situ measurements of ocean circulation at the same time that altimeters and scatterometers will be flown in space on the European Space Agency's (ESA) ERS-1, the U.S./French

TOPEX/Poseidon spacecraft, and the Japanese ADEOS satellite. The first pilot studies of the hydrological cycle under the Global Energy and Water Cycle Experiment (GEWEX) are planned to be carried out at the same time as the flight of the proposed Tropical Rainfall Measurement Mission (TRMM). The major studies of GEWEX are proposed to be carried out at the same time as the EOS program.

However, an overall strategy for in situ measurements in the time frame of EOS has not been developed. Because of the long lead time necessary for such planning, we conclude that the agencies involved in the USGCRP should begin to develop the plan soon. Without a carefully planned in situ program, including international participation, much of the USGCRP will not be able to take full benefit of EOS and other space-based measurements.

EOS IN THE CONTEXT OF OTHER SPACE MISSIONS

While EOS will provide an essential part of the total set of observations required for the U.S. Global Change Research Program, not all the environmental parameters required for understanding global change that can be measured from space can be measured by the EOS spacecraft.

Therefore, EOS must be viewed in the context of other space-based measurement systems of both the U.S. and other nations participating in global change research that will fly either before or concurrently with EOS. Some parameters must be measured by space-borne instruments on other satellites and in other orbits. The full set of space-based observations that will contribute to improved understanding of global change are expected to be made by EOS together with numerous other spacecraft. These include NASA research programs such as UARS and TOPEX/Poseidon, the Earth Probes series, and instruments on Shuttle flights, as well as NOAA and DOD operational satellites, and operational and research satellites launched by other nations.

An overall international observational strategy that includes all these research and operational satellites and instruments has been discussed, but not yet developed. (See, for example, *IGBP Needs for Remote Sensing in the 1990s and Beyond*, a forthcoming report from the Special Committee for the IGBP.) There is a sense of the missions that the respective nations or agencies would like to fly, but there are also uncertainties. An international strategy would be useful for ensuring the continuity of observations (see Chapter 7 on Continuity and Reliability) and the efficient use of resources. Because NASA has taken the lead in developing the remote-sensing technology for global change research, the agency, working within the CEES, should also take the lead in developing an international strategy for space-borne measurements of global change.

EOS AND THE USGCRP

In order to assess the contributions of EOS to the measurements of environmental parameters necessary for documenting global change, it must be recognized that EOS is only part of the space-based system required and that the space-based observations are only part of the total space-based and in situ measurements required.

EOS is currently designed to provide a 15-year series of measurements from a sun-synchronous polar orbit with a set of highly developed instruments. Such instruments will have higher spectral resolution by orders of magnitude than any available today or likely to be available in the near future. In addition, EOS instrumentation will include advanced versions of existing operational instruments for continuity of measurements. By flying several of these instruments simultaneously, NASA plans to achieve a major improvement in the description of global physical and biogeochemical phenomena. The global change research community looks to EOS to provide new technology for measuring parameters not adequately studied today, as well as to continue the measurements of parameters that are reasonably well understood. The objective is for EOS to provide the user community (science, industry, policy) with the first comprehensive long-term measurement and data system specifically aimed at global change issues.

The proposal for a 15-year series of satellites focused on study of the Earth raises issues of programmatic strategy. EOS has a dual character, combining typical research missions with others that have more of the characteristics of operational monitoring missions, such as those flown by NOAA and DOD. Research missions are typically strongly dependent on a few individuals who devote portions of their careers to them, whereas operational missions are designed to deliver data to other users on a reliable and routine basis. Because all EOS data are intended to be widely shared, a more operational strategy is required—even for the pure research objectives. Furthermore, the general strategy and the specific instrument details and algorithms should be fully documented.

During the development of the EOS concept, NASA formed a Science Steering Committee that produced the volume entitled *From Pattern to Process: The Strategy of the Earth Observing System.* That report proposed the implementation, individual measurements, and synergistic measurement strategies for EOS. In the interim, however, much has changed. New instrument concepts have been developed; others have been discarded. A competitive selection process has been conducted naming instrument investigators and teams to perform interdisciplinary studies. A budget profile now defines a funding envelope for investigators, instruments, and spacecraft.

It is now vital to begin the process of updating the earlier work of the Science Steering Committee to develop the successor to *From Pattern to Process*. As indicated earlier, the successor should detail the observational strategy for space-based observations and the ancillary in situ and ground-based measurements that accompany them. The required strategy would go beyond *From Pattern to Process*, however, in that it should include in situ measurements. Consequently, while NASA should participate in its preparation, responsibility for its development should fall to the CEES.

The GEWEX program provides an example of a coordinated international observational strategy to support research of the type envisioned. GEWEX relies first on limited in situ and satellite (TRMM) observations for a pilot study to be followed by an extensive ground-based measurement program complemented by EOS data.

The observational strategy should indicate how each observing system and measurement contributes to the overall scientific objectives of the USGCRP. In particular, it should show how each measurement, with its associated accuracy and resolution in space and time, will contribute the desired end product of global or regional data sets that will advance our understanding and predictive capability of the Earth system. Perhaps most important, it should allow for the evolution of observational goals and technology and should be updated from time to time. We can refer to this documentation as providing "traceability".

The new study must scrupulously state the objectives and rationale for the deployment of the series of instrument suites, and provide with refereed journal care the traceability to the detailed assumptions and analyses upon which the objectives and rationale are based. As the study evolves and changes, it is important that the strategy be comprehensive and clear. Changes stemming from either scientific, technological, or financial reconsideration of the mission must be understood and thoroughly documented.

The simplest statement of the objective of the EOS program is that it will advance mankind's understanding of the continuing evolution of the planet. Unlike most scientific investigations, the value of EOS will lie in its aggregate accomplishment, rather than in the important but individual achievements of the respective investigator teams. Thus documentation that aids and guides the aggregate accomplishment, to which newcomers can also refer, is vital. Therefore, we recommend that NASA initiate immediately the development of a documentation plan, and quickly thereafter the documentation itself that will be required in this multidecadal program.

Summary Recommendations

In view of the fact that EOS is a 15-year program, a fully-documented strategy and specification of instruments must be developed and updated as required. This is the only way that EOS can serve as an intermediate step between the research missions of the past and the operational systems of the future.

As indicated earlier, the set of instruments under consideration for flight appears to be capable of providing a comprehensive set of measurements of high priority environmental parameters. The complete set of measurements eventually to be made from EOS spacecraft will depend on the successful development of the respective instruments, as well as on other factors. In the sections below, we briefly summarize the contribution of EOS measurements to the objectives of the USGCRP. It should be noted at the outset that specific agency planning will not necessarily have the same framework as that developed by the USGCRP, but the specific elements of agency programs should be relevant to the overall framework. Each of the specific elements of the EOS scientific plan contributes to one or more of the elements of the USGCRP.

Because EOS has been proposed as a major contribution to the USGCRP, the overall strategy for the program and the selection of instruments and orbit should be optimized on the basis of USGCRP priorities. Review processes should be set up to ensure that this close connection is made and maintained.

A clear strategy and process should be established by which instruments are selected. This strategy would determine the measurements to be made and, therefore, the individual and aggregate research to be done. The specific research objectives, and possibly even the general goals, of the USGCRP will change as more is learned about the subject. The technology of remote sensing is also likely to change over the life of the program. Although continuity of specific data sets will be an important consideration, it may be desirable to alter the instruments or the platforms, or both, at some time in the future. Currently, the program contains no process that would enable it to evolve in response to new scientific understanding or technological developments.

CONTRIBUTIONS TO SPECIFIC USGCRP SCIENCE PRIORITIES

Because we have been asked to consider the contribution of EOS to the USGCRP, we use the set of priorities listed in the FY 1991 version of *Our Changing Planet*. The USGCRP framework provides for specific science priorities in seven interdisciplinary areas: (1) climate and hydrologic systems; (2) biogeochemical dynamics; (3) ecological systems and dynamics; (4) Earth system history; (5) human interactions with the Earth system; (6) solid Earth processes; and (7) solar influences. NASA has described its program in slightly different terms.

As currently planned, EOS data are expected to contribute in a major way to areas (1), (2), (3), and (6); less extensive contributions are expected to be made to areas (4), (5), and (7). The specific contributions are discussed in the sections below. In each section we quote the policy-relevant questions as noted in the FY 1991 version of *Our Changing Planet*, and then summarize current plans and proposals for space missions to address them, including the proposed EOS contributions. In the discussion of particular instruments, it should be noted that in some cases the process of selecting between competing instruments is still under way. In every case, we emphasize that we refer to the generic class of instrument represented by the particular example cited; naming a specific instrument is not to be taken as an endorsement of that instrument over competing instruments for flight on EOS.

Climate and Hydrologic Systems

1. What is the role of clouds in the Earth's radiation and heat budgets?

Near-Term Plans

The ongoing programs for monitoring the Earth's radiation budget, the Earth Radiation Budget Experiment (ERBE) and the International Satellite Cloud Climatology Program (ISCCP), if continued until the launch of EOS, will provide continuity for this important parameter, which is one of the principal diagnostics of the "greenhouse" effect. To monitor the Earth's radiation budget properly, daily global data from two polar orbits (a.m. and p.m.) and a mid-latitude inclined orbit (50 to 60 degrees) are required.

It should be noted that a joint French/Soviet radiation experiment, the Scanner for Radiative Budget (SCARAB), is scheduled to be flown in 1991. This experiment will help to provide a follow-on to ERBE in the early 1990s. Unless another Earth radiation budget measurement mission is flown, however, there will be a several year gap in such data between the end of the SCARAB mission and the beginning of EOS.

EOS Plans

The EOS instrumentation makes a major contribution to answering the question about the role of clouds in climate. The high degree of temporal and spatial variability of cloud-atmosphere radiation interactions and fluxes of heat and energy at the surface must be measured accurately. The EOS instruments promise to provide accurate atmospheric temperature profiles with the Atmospheric Infrared Sounder (AIRS) and the Advanced Microwave Sounding Unit (AMSU). The current atmospheric temperature and water vapor profiles provided by the operational HIRS/AMSU system constitute valuable data where other measurements are sparse, as in the southern hemisphere. To date, however, they have proved to be of less utility where dense networks of in situ observations exist. The instruments proposed for EOS promise higher spatial and spectral resolution as well as improved accuracy.

The Clouds and Earth's Radiant Energy Systems (CERES) radiometer is designed to determine broadband shortwave and long-wave top-of-atmosphere radiances. The High-Resolution Microwave Spectrometer Sounder (HIMSS) would establish water content of clouds over the ocean. The Moderate Resolution Imaging Spectrometer (MODIS) in its nadir looking mode is intended to provide spectral information needed for determining physical cloud properties and cloud height. The Earth Observing Scanning Polarimeter (EOSP) would determine aerosol composition. The Multi-angle Imaging Spectro-Radiometer (MISR) promises, through its multi-angle viewing capability, to provide the bulk radiative properties of aerosols in the shortwave spectral region.

The current plan for EOS has adequate instrumentation for monitoring the Earth's radiation budget from a p.m. polar orbit. Data from an a.m. polar orbit could be provided by the European Polar Orbiting Platform (EPOP) or the NOAA polar orbiting satellite series. An inclined-orbit instrument is planned for the Space Station, in a tropical orbit. At 28 degrees, the inclination of the Space Station's orbit is too low to complement coverage in the high latitude regions. Moreover, uncertainties in the time of the Space Station launch may reduce coverage unacceptably.

EOS includes plans to monitor solar output with the Solar Stellar Irradiance Comparison Experiment (SOLSTICE) and the Active Cavity Radiometer Irradiance Monitor (ACRIM). SOLSTICE would provide precise daily measurements of the full disk solar ultraviolet irradiance; ACRIM would monitor the variability of total solar irradiance with state-of-the-art accuracy and precision.

Finding

A gap in measurements of the Earth's radiation budget will occur in the mid-1990s if no additional mission is proposed. A follow-on to the SCARAB experiment at an adequately inclined orbit will be needed. Such a mission would be suitable for the Earth Probes series.

2. How do the oceans interact with the atmosphere in the storage, transport, and uptake of heat?

Near-Term Plans

Before EOS is available, a number of remote sensing missions are expected to study ocean circulation and air-sea fluxes of energy and momentum. They include the precision altimetry mission, TOPEX/Poseidon; the sea-surface temperature measurements, altimetry, and a surface wind measuring scatterometer on the European Space Agency's ERS-1; the NASA scatterometer on the Japanese ADEOS; and an altimeter to be flown by the U.S. Navy on a Special Purpose Inexpensive Satellite (SPINSAT). These are to be complemented by ongoing operational measurements of sea surface temperature and humidity from the NOAA and Defense Meteorological Satellite Program (DMSP) programs. The various missions are intended to provide data for existing and planned field programs such as the World Ocean Circulation Experiment.

EOS Plans

The primary EOS measurements are intended to provide a variety of data on ocean currents, surface winds, ocean and atmospheric temperatures, and near-surface humidity for air-sea flux studies. They include sea-surface temperature from the Moderate Imaging Spectrometer in its nadir mode, and from the High Resolution Microwave Spectrometer Sounder. Both the classical fan-beam (STIKSCAT) and advanced dual pencil-beam (SCANSCAT) scatterometer designs are being considered for EOS. Surface topography would be measured from an altimeter. Air temperature and humidity near the sea surface would be measured with the Atmospheric Infrared Sounder and the Advanced Microwave Sounding Unit.

3. How will changes in climate affect temperature, precipitation, and soil moisture patterns, and the general distribution of water and ice on the land surface?

Near-Term Plans

Specific missions proposed in this general area are the joint U.S./Japanese Tropical Rainfall Measuring Mission (TRMM) and a planned French mission, Bilan Energetique de la Système Tropicale (BEST). Each mission proposes to carry a major radar sensor for measuring rainfall directly, and together they would form the space-based portion of the Global Energy and Water Cycle Experiment, which is scheduled to begin in the mid-1990s. Of the two satellite projects, TRMM is more fully developed in its technical planning.

EOS Plans

The primary EOS measurements in this area are for temperature and water vapor sounding from AIRS and AMSU. Precipitation, sea ice, and

Spectrometer Sounder (HIMSS). Glacier profiles would be measured by the Geosciences Laser Ranging System (GLRS). Water vapor fluxes would be monitored by the scatterometer and HIMSS over the oceans. Over land, tropospheric winds, aerosols, and cirrus clouds would be monitored by the Laser Atmospheric Wind Sounder (LAWS). Vegetation characteristics would be measured by the Moderate Resolution Imaging Spectrometer (MODIS), the High Resolution Imaging Spectrometer (HIRIS), and the Intermediate Thermal Infrared Radiometer (ITIR).

Recent aircraft flights demonstrate that soil moisture can be measured from space with a Synthetic Aperture Radar (SAR). Monitoring soil moisture is important for study of the hydrologic budget, but is not included in current EOS plans because of budget considerations. Although soil moisture can—and should—be measured on the ground, only satellite measurements can provide global coverage continuously. The LAWS instrument will also require extensive development of technology to achieve the highest level of proposed precision.

Engineering considerations presented by NASA suggest that the SAR instrument contemplated for EOS would not be compatible with a multi-instrumented satellite. Therefore, the potential contributions of a free-flying SAR mission should be carefully considered in the context of global change research.

4. How can the reliability of global-and regional-scale climate predictions be improved?

The EOS and other space-based observing missions are expected to make major contributions toward answering this question in a number of ways. First, improved understanding of processes obtained from the respective missions would be incorporated into better process descriptions in models. Second, data from the missions—either archived directly or assimilated into the data streams of current global weather prediction systems—would provide climate data sets invaluable for validating models to be used for projecting climate change. Third, many of the boundary conditions for models used for climate projections must be derived and improved from satellite observations. Finally, predictions for the satellite data can provide initial conditions needed for the shorter seasonal to interannual time scales.

Biogeochemical Dynamics

1. What is the relative importance of the oceans and terrestrial

biosphere as sinks for fossil fuel carbon dioxide, and how do they change with time?

Near-Term Plans

Monitoring the distribution of oceanic chlorophyll and the properties of terrestrial vegetation provides information on gas and nutrient exchange between the atmosphere and ocean, freshwater and terrestrial biosphere, and on oceanic and terrestrial carbon storage. The role of biological systems in global change is one of the least understood. The precursor missions and the EOS planning in this area are key parts of the global change research program and should have high priority.

The international Joint Global Ocean Flux Study (JGOFS) has been developed and has a field program now beginning. Currently, the Seaviewing Wide Field Sensor (Sea WiFS) ocean color mission is planned to support JGOFS. Flight of the Shuttle Imaging Radar (SIR-C) is important for studies of land vegetation, and will be complemented by field studies of the World Climate Research Program (e.g., the International Satellite Land Surface Climatology Program and the Global Energy and Water Cycle Experiment) and the International Geosphere-Biosphere Program (e.g., the Joint Global Ocean Flux Study).

EOS Plans

The Moderate Resolution Imaging Spectrometer (MODIS) in both its nadir-viewing (MODIS-N) and side or tilt-viewing (MODIS-T) implementations is the essential next step for measuring ocean and land chlorophyll concentration. The high spectral resolution of the MODIS is intended to provide measurements not possible before. The MODIS, the high spectral resolution HIRIS, the Intermediate Thermal Infrared Radiometer (ITIR), and the Multi-Angle Imaging Spectro-Radiometer (MISR) are expected to collect land vegetation measurements. Biogenic gas emissions could be measured by the Tropospheric Emission Spectrometer (TES), and vegetation structure could be monitored with the NASA SAR.

Findings

Current plans omit important space-based measurements that would be valuable for understanding the relative importance of ocean and terrestrial ecosystems as sinks for carbon dioxide. First, in the near term, the JGOFS program would benefit from the flight of the next generation of ocean color instrument, the proposed Sea WiFS. Second, the SAR has potentially important roles to play in making measurements of biological processes on land.

2. What are the major sources responsible for the current increases in atmospheric nitrous oxide and methane?

3. What are the implications for stratospheric ozone—globally and in polar regions—of increased concentrations of chlorine and bromine?

Near-Term Plans

In the near term, the Upper Atmosphere Research Satellite (UARS) and the continuing in situ Global Tropospheric Experiment (GTE)—with its Pacific Exploratory Mission in 1991 and an Atlantic program in 1992—will address these two questions in the interval before the first EOS satellite is launched.

EOS Plans

For these studies, it is important to monitor solar radiation to the earth. It is proposed that solar output be monitored by the Solar Stellar Irradiance Comparison Experiment (SOLSTICE) and the Active Cavity Radiometer Irradiance Monitor (ACRIM). SOLSTICE should provide precise daily measurements of the full disk solar ultraviolet irradiance; ACRIM is designed to monitor the variability of total solar irradiance with state-of-the-art accuracy and precision.

The Tropospheric Emission Spectrometer is proposed to measure tropospheric trace gas species. This high-resolution infrared imaging spectrometer would generate three-dimensional profiles on a global scale of virtually all infrared-active species from the surface to the lower stratosphere. The Measurement of Pollution in the Troposphere (MOPITT) and Tropospheric Radiometer for Atmospheric Chemistry and Environmental Research (TRACER) instruments are intended to monitor carbon monoxide in the troposphere.

The High-Resolution Dynamics Limb Sounder (HIRDLS) is expected to observe the global distribution of temperature and concentrations of ozone, water vapor, methane, various oxides of nitrogen, CFCs, and aerosols in the upper troposphere, stratosphere, and mesosphere.

The Spectroscopy of the Atmosphere Using Far Infrared Emission (SAFIRE) instrument is in ended to provide simultaneous measurements of HO, NO_x, ClO_x and BRO_x species. The Microwave Limb Sounder (MLS), an enhanced version of an instrument on UARS, would provide vertical profiles of all molecules and radicals believed to be important in the ozone destruction cycle in the stratosphere and mesosphere. The Stratospheric Wind Infrared Limb Sounder (SWIRLS) is expected to provide direct measurements of stratospheric winds by measurements of Doppler shift. This would allow correlation of atmospheric dynamics and chemistry in the stratosphere. Together with the Stratospheric Aerosol and Gas Experiment

(SAGE III) instrument, a full set of data should be provided to help answer questions about these phenomena.

Ecological Systems and Dynamics

1. What ecological systems are most sensitive to global change, and how can natural change in ecological systems be distinguished from change caused by other factors?

2. What are the likely rates of change in ecological systems because of global change, and will natural and managed systems be able to adapt?

3. How do ecological systems themselves contribute to processes of global change?

Near-Term Plans

The satellite data required to address the above questions comes in the near term from research and operational missions. The ongoing NOAA/AVHRR, Landsat, and SPOT programs provide detailed information on ecological systems primarily on land. Data from these programs can be used to monitor changes in land use patterns and the areal extent of vegetation representative of ecosystem types. As described earlier, current proposals include the flight of an ocean color instrument.

EOS Plans

The EOS contribution to these research objectives should be made by the same instruments that are intended to contribute to research on biogeochemical dynamics: MODIS-N and -T, HIRIS, MISR, and ITIR. The SAR instrument, which could make additional contributions in this area, is not included in current plans for EOS. The EOS instruments would provide data similar to those of the NOAA/AVHRR, Landsat, and SPOT programs but with higher spectral resolution and accuracy for studying ecological processes in detail.

Earth System History

1. What are the natural ranges and rates of change in the climate and environmental systems?

2. How rapidly have ecosystems adapted to past abrupt transitions in climate?

3. Do past warm intervals in Earth history provide appropriate scenarios to test model predictions of future global warming?

The answers to these questions are expected to come primarily from in situ studies of cores from continental, ice, and ocean drilling. Current space-based observations cannot directly reveal global changes in the Earth's history, but they can provide data useful for improving understanding of solid Earth processes, which would help to illuminate that history. (See the section on Solid Earth Processes below.)

Human Interactions

1. What kinds of empirical data are needed to measure and understand human interactions in global change?

The EOS program should provide data that will be potentially useful for the human interactions aspect of the USGCRP. For example, the very high resolution instruments such as HIRIS could provide information on direct human interactions with the environment (e.g., deforestation, coastal and estuarine pollution, agricultural practices). EOSDIS is expected to be an important source of such data for the study of the effects of human activities on the environment. In order that the use of these data be effective, there will be a need for close interaction between researchers who will use these data for this purpose and the EOSDIS designers to ensure that the system provides the required information.

2. How and why do human beings and human systems influence physical and biological systems?

The answer to this question will depend partly on the use of satellite data, which can provide an important means of studying and monitoring the effects of some human activities on the environment.

Solid Earth Processes

1. How do different coastal regions respond geologically and ecologically to higher sea level, and how can the contributions from changes in climate (e.g., glacier melting and ocean warming) be differentiated from those due to tectonic processes?

2. What are the magnitude, geographic location, and frequency of volcanic eruptions and their effect on climate?

3. How do permafrost regions of the Northern Hemisphere respond to climate warming?

Near-Term Plans

The near-term activities in this area include the precise positioning provided by the Global Positioning System, the Very Long Baseline Interferometry, and Laser Tracking of the LAGEOS I and II satellites. These missions support the use of global tide gages and satellite altimeter measurements of sea level change, as well as altimeter measurements of changes in global ice mass. Imaging of volcanoes and other regions will be provided by various operational satellites (AVHRR on the NOAA satellites and imagers on Landsat and SPOT). Emissions from volcanic eruptions will be monitored by the operational meteorological satellites and the SAGE instruments. Beginning in 1991, UARS will provide useful data on the stratosphere.

EOS Plans

Crustal movement and tectonic plate deformation are proposed to be monitored by the Geoscience Laser Ranging System (GLRS), which will carry a laser system, an optical tracking system, and a precise navigation system for use with arrays of reflectors on the ground. The Altimeter and Global Positioning System Geoscience Instrument (GGI) should be a source of accurate ice and ocean topography. The SAR, which is currently not budgeted, could provide all-weather studies of surface processes.

Surface mineral identification, soil characteristics, and geothermal monitoring would be carried out with the ITIR and HIRIS. Monitoring of trace gases and aerosols is intended to be done with SAGE, TES, and HIRIS.

EOS data should be useful in characterizing the nature of volcanic emissions, for monitoring the mechanisms of plate motion over long periods, and for understanding regional uplift, subsidence, and associated coastal processes. Changes in the Earth's rotation and length-of-day could be monitored by EOS with high resolution geodetic techniques, while the deep-seated processes in the Earth that cause these changes may be inferred from studies of the Earth's magnetic field. EOS sensors are expected to monitor surface processes and detect areas of current or potential desertification and erosion.

Solar Influences

1. What aspects of solar variability are influencing the stratospheric ozone layer?

2. What impact do other inputs, e.g., particles, have on the upper atmosphere and how are they coupled to other atmospheric regions?

3. How does the sun's output vary and what is its impact on terrestrial climate?

Near-Term Plans

Providing answers to these questions will require accurate measurements of solar variability at all wavelengths and continuing monitoring of appropriate chemical species in the upper atmosphere. These measurements are being made by NOAA operational satellites. Near-term plans include instruments on UARS, as described earlier in connection with the discussion of biochemical dynamics. The data are needed for further development of theoretical models of solar-terrestrial interactions that affect global change.

EOS Plans

Of particular importance here is ultraviolet radiation from the sun. The EOS Solar Stellar Irradiance Comparison Experiment (SOLSTICE) is intended to monitor the full disk solar ultraviolet irradiance as a follow-on to a similar instrument carried by UARS.

The EOS Stratosphere Aerosol and Gas Experiment III (SAGE III) is proposed to measure profiles of aerosols, air density, and a number of constituents. It is an extension of the successful SAGE experiments flown earlier and planned for UARS. SAGE III is also planned for flight on the Space Station to provide full coverage and back-up measurements.

EOS proposes to measure solar irradiance with a radiometer (the Active Cavity Radiometer Irradiance Monitor) and with an ultraviolet irradiance measurement. Each of these is a source of continuity with UARS measurements.

6

Simultaneity of Data Collection

EOS is premised on the assumption that it is essential to collect global data on various environmental parameters simultaneously. How important is data simultaneity to the ultimate utility of the data? Can the requirement of simultaneity be applied more narrowly than proposed?

We conclude that arguments for collecting certain sets of data simultaneously are strong. The arguments, which do not apply to all the measurements that NASA proposes to make with EOS, depend primarily on the importance of studying the interactions within natural processes occurring on short time scales and on the interdependence of certain pairs or small sets of measurements for precise quantitative interpretation. For measurements critical to two high priority areas of research in the USGCRP, the needs for several small sets of instruments to make simultaneous measurements lead to a set of interwoven requirements for a suite of ten instruments that should be flown on the same satellite. (See the section below on Specific Analyses for Particular Scientific Objectives.)

The instruments proposed for EOS and certain other space missions that are planned to be flown in the interim or contemporaneously with EOS are consistent with the scientific objectives for observing the Earth system developed in a series of reports from the NRC and elsewhere (*Earth System Science: A Program for Global Change;, Earth Science from Space; Strategy for Earth Explorers in Global Earth Science; Mission to Planet Earth*). The strategy is best summarized in *Mission to Planet Earth*, a volume in the

Space Studies Board series, *Space Science in the Twenty-First Century*, which concluded that "the measurements must be *global and synoptic*, they must be carried out over a *long term*, and different processes. . .must be measured *simultaneously* (to a degree dependent on the rates involved)."

		Spatial Coincidence	
		Same Area Same View Path	Same Area Different View Path
TEMPORAL COINCIDENCE	Same Time (Few Sec.)	Congruent	Simultaneous
	Close to Same Time (Few Min.)	Close Sequential	
	Different (> 10 Min.)	Sequential	

Figure 1
Nomenclature for "Simultaneity."

DEFINITIONS OF SIMULTANEITY

"Simultaneity" takes on several meanings when applied to EOS. In this report, we adopt the terminology of the EOS Investigators Working Group (see Figure 1).

In the current context, we take "simultaneous" to mean "within a few seconds." There is a more stringent requirement in several instances for "at the same time through the same atmospheric path," i.e., essentially "bore-sighted." There are also some special requirements for "at nearly the same time but through different view paths, i.e., different look angles." Given the above, observations taken within a few seconds of the same area on the surface through the same view path are termed "congruent"; those acquired at the same time of the same area but through different view paths are termed "simultaneous"; those acquired within a few minutes of the same area are termed "close sequential." Observations of a common area obtained at intervals greater than about ten minutes are termed "sequential."

The most stringent requirement would be for "congruent" observations, the least stringent for "sequential." But there are some special situations that require specifically "close sequential" observations made through different view paths.

Several specific remote sensing studies illustrate the differences in nomenclature. For example, the Large Area Crop Inventory Experiment (LACIE) and AgriSTARS (former interagency programs to establish applications of remote sensing to agriculture and other plant canopies) were based primarily on sequential observations using the same instrument (the Multi-Spectral Scanner on Landsat). Recent studies of global deforestation and desertification have been based primarily upon sequential measurements obtained with the NOAA Advanced Very High Resolution Radiometer (AVHRR) and the Landsat Thematic Mapper. In contrast, global temperature soundings for weather forecasting are made by truly congruent measurements by the High Resolution Infrared Radiation Sounder (HIRS) and the Advanced Microwave Sounding Unit (AMSU) on the NOAA polar orbiters. NASA's Ocean Topography Experiment (TOPEX) requires congruent dual frequency measurements of altitude and a separate measurement of water vapor, the latter for correcting the effects of water vapor on the former.

GENERAL CONSIDERATIONS

Four lines of argument enter into consideration of the need for simultaneous or congruent measurement of parameters. First, understanding natural processes that change on time intervals of seconds to minutes may require measurements of several different simultaneously interacting parameters. Second, the physics of the techniques for interpreting some measurements depend on environmental conditions that can be sensed with companion instruments. For example, data from surface imagers must be corrected for atmospheric moisture. Environmental conditions have different degrees of persistence; some, such as atmospheric moisture, can vary on time scales of seconds to minutes, so that companion measurements should be congruent. Where congruent measurements are required but not made, no amount of subsequent data processing can recover the full information. Third, merging sequential data streams can place additional technical and financial burdens on ground-based data management and computational systems that might not be present if the data were taken simultaneously. Fourth, engineering considerations—such as the availability of launch vehicles, onboard electrical power, viewing angles, and data transmission capabilities—affect decisions on spacecraft size, complexity, reliability, and cost. In some cases, there can be advantages to larger spacecraft systems that make possible simultaneous measurement with a number of instruments. At the same time, these considerations must be balanced against possible scientific disadvantages, such as requiring all the instruments to fly on the same orbit. Such a requirement may not be optimal for some measurement objectives and may not provide the flexibility needed to protect continuity in the case of a sensor or system failure. The latter are discussed below in our response to question 3.

To Enhance Process Studies

It is a rare natural process that involves only one parameter or takes place on only one spatial scale. Thus there are strong arguments that, to understand natural processes, measurements of several parameters on several spatial scales must be taken.

In studying many global change processes, congruent imaging surveys are required at variable spatial and spectral resolutions. For example, congruent acquisition of MODIS and HIRIS imagery would provide large and small images in the same field of view. As the successor to AVHRR, MODIS (which has a pixe 1 size of 1 km) will provide gross spatial variations in surface-cover materials on a global scale. Before they can understand processes, scientists must be able to identify the nature and condition of surface materials at higher spatial and spectral resolution. Ideally, global patterns could be inferred by simply averaging measurements of this type. The acquisition of global imaging surveys at HIRIS resolution (pixel size, 30m), however, is not practical from an engineering standpoint. Consequently, it is logical to develop a two-sensor system, one for global-scale measurements (MODIS), and another for detailed regional-scale studies (HIRIS). To use the instruments for process studies, congruent measurements are necessary.

The requirement for congruency of MODIS and HIRIS observations results from two lines of reasoning. First, the same surface materials must be observed by both sensors. Many surface materials such as crops, scrub brush, flowering plants and trees, and suspended sediments in surface waters can change character significantly over time periods that are short relative to the repeat cycles of a single spacecraft. Further, the spectral signatures of the sensed objects often vary with the angle of the sun, or the angle of observation of the instrument. Second, before a detailed analysis within the global view can be made, HIRIS measurements must usually be taken within the field of view of the MODIS sensor. In principle, this could be accomplished by placing the sensors on two different satellites that would follow one another closely in orbit while maintaining their relative positions (i.e., flying in formation or position keeping). However, the NASA analysis suggests that the simplest means of assuring spatial coregistration of HIRIS and MODIS data is to place the two instruments on a common spacecraft so that they will use the same view path for their observations.

To Interpret Physical Measurements

As a general rule, no single measurement of radiance will allow the calculation of a geophysical parameter. For example, to measure accurately the distance traveled (by the signal) from a radar altimeter, from which altitude is inferred, signals at two frequencies are needed to correct for the influence of the ionosphere, and an independent measurement of water vapor in the atmosphere is needed to correct for influences of the atmosphere. Another example is the derivation of parameters on the surface of the Earth from an optical imaging instrument, which generally requires several optical frequencies and independent corrections for water vapor and particulates in the atmosphere. Several other examples are described in the NASA documentation of EOS instruments and research projects. Because these measurements must largely be taken of the same atmospheric column, and because the atmosphere changes on the time scale of minutes, the measurements must be congruent.

To Facilitate Data Management

Merging sequential data streams places technical and financial burdens on ground-based data management and computational systems in addition to those that would be present if the data were taken simultaneously. For instance, co-location of pixels from the NOAA Geostationary Operational Environmental Satellite (GOES) with soundings from the NOAA polar orbiters has proven too difficult to automate. However, in the current GOES system there is a crude sounding capability done with the same instrument. The soundings can be registered with the images and corrections or correlations can be made that add to the usefulness of the images.

To Incorporate Engineering Considerations

As a practical matter, planning space missions must take into account a number of engineering and systems considerations. For example, the platform that supports the research instruments must have technological and logistical capabilities compatible with the payload. Technical capabilities affect the extent to which the scientific objectives of missions can be achieved.

A major technical constraint appears to be in launch capacity. According to the current capabilities and plans of the U.S. launch industry as supplied to us by NASA, only two vehicles—Delta-II and Titan-IV—are expected to be available to launch into polar orbit from the Western Test Range facility in the late 1990s. The satellite design is therefore constrained in size, shape, and mass by the fairings of the vehicles. If scientific arguments were sufficiently strong, an intermediate launch capability, Atlas-IIAS, might be established at that facility, but it seems likely that the EOS program would have to incur the full costs in the absence of other users. Launch capabilities continue to evolve, however; and to the extent that the EOS program evolves, it should incorporate ways to consider the opportunities that other launch systems afford. (See the section in Chapter 7 on Launch Vehicles.)

Flying a number of optical instruments on the same platform may have significant systems and scientific advantages in terms of calibration. Calibration of space instruments has, for years, been recognized as an important concern. Drift and lack of intercalibration of instruments have been a barrier to comparison of data from different satellites and can prevent quantitative analysis of potentially long-time series obtained by combining data from different missions. Historical measurements of stratospheric ozone, sea surface temperature, and atmospheric temperature are three examples. One way to calibrate optical instruments is to compare instruments flown at the same time looking at the same dark or bright scene on the surface. Means to obtain an absolute calibration of one of the instruments are essential to this technique. For example, instruments might be intercalibrated with MODIS-T, which can be tilted to view dark space and the moon.

Flying a number of instruments on the same platform may have scientific disadvantages related to the selected orbit. In principle, every instrument has a preferred orbit and few of these preferred orbits are identical. Altitudes, inclinations, sun synchrony, equator crossing times, and repeat times all affect the quality of the information derived from instruments. Thus flying several in the same orbit entails compromise for each. For example, the projected orbit for EOS detracts from the ability of ALT to measure mean ocean circulation and from the ability of all instruments to monitor diurnal variations and cycles. Some of these disadvantages may be overcome by relying on data from complementary missions, as might be done in missions under consideration for the Earth Probes series or on operational satellites. Engineering considerations are discussed in greater detail in Chapter 7.

SPECIFIC ANALYSES FOR PARTICULAR SCIENTIFIC OBJECTIVES

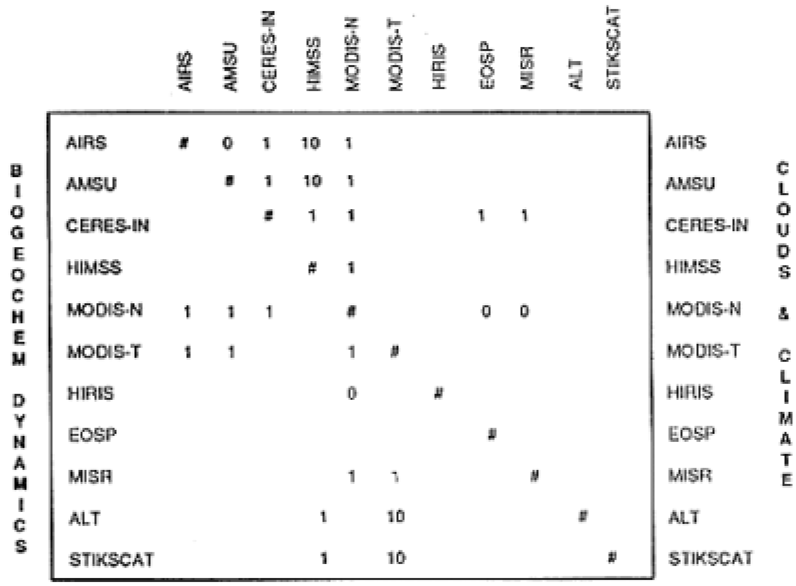
The most thorough assessment of requirements for synergism among measurements that we have seen is contained in a draft letter report to NASA's Associate Administrator for Space Science and Applications from the Chair of the Payload Advisory Panel (PAP) of the EOS Investigator Working Group (B. Moore, private communication, April 2, 1990). The assessment focuses on two of the high priority global change research issues: the role of clouds in climate and hydrological systems and the flux of trace gases among the biosphere, atmosphere, and oceans. In the analysis, which is summarized below, the PAP traces the needs for instruments from the geophysical measurements, through the combinations needed to make those measurements, to specific requirements for simultaneity or near simultaneity.

Climate and Hydrological Systems: the Role of Clouds

Understanding the role of clouds is crucial to improving general circulation models that simulate climate change. The PAP analysis notes that the liquid water content of clouds, their optical characteristics, and the extent of cloud cover all have important effects—sometimes conflicting—on the results of model simulations. Therefore, to improve the models, the PAP analysis concludes that it is important to obtain data on the optical, geometrical, and microphysical properties of clouds on a global basis. Parameters of interest include: optical thickness, emissivity, effective radius of cloud particles, atmospheric pressure at the tops of clouds (or their altitude), cloud top temperature, and the phase of cloud water (ice, snow, and/or liquid water). In most cases, the high temporal and spatial variabilities of many of these parameters require that their measurement be taken at about the same time because the average of the computed properties cannot be determined as a function of the averages of the measured parameters. The PAP notes, for example, that mid-level clouds move at 20 to 40 m/s so that if the CERES instrument, with 25 kilometer pixel, and the MODIS, with pixels less than 1 kilometer, must look at the same scene, they must take measurements within three minutes (i.e., close sequential) to assure 80 percent coherence. The HIRIS pixel is to be 30 meters on a side.

Atmospheric temperature profiles are measured by AIRS and AMSU-A and -B; radiances at the tops of clouds are measured by CERES-IN; oceanic cloud water and water vapor are established by HIMSS; basic physical properties of clouds, including heights, are obtained from MODIS-N; aerosol composition is determined from EOSP; and bulk radiative properties of aerosols in the short-wave spectral region are provided by MISR. The PAP concludes that overall consistency among the cloud properties, humidity, temperature, and radiance measurements requires that the 8 instruments make essentially simultaneous measurements. Because of their larger pixel size, HIMSS and AIRS/AMSU-A and -B can be separated by as much as ten minutes.

Thus to obtain these measurements, this set of instruments must view through the atmosphere either congruently, within a few minutes, or within ten minutes of each other. From the PAP analysis and our own discussions, we constructed a set of order-of-magnitude simultaneity requirements for the several instruments listed above for clouds and climate studies (see the upper right side of Figure 2).



	AIRS	AMSU	CERES-IN	HIMSS	MODIS-N	MODIS-T	HIRIS	EOSP	MISR	ALT	STIKSCAT	
AIRS	#	0	1	10	1							AIRS
AMSU		#	1	10	1							AMSU
CERES-IN			#	1	1			1	1			CERES-IN
HIMSS				#	1							HIMSS
MODIS-N	1	1	1		#			0	0			MODIS-N
MODIS-T	1	1			1	#						MODIS-T
HIRIS					0		#					HIRIS
EOSP								#				EOSP
MISR					1	1			#			MISR
ALT				1		10				#		ALT
STIKSCAT				1		10					#	STIKSCAT

NOTE: Numbers are approximate allowable delays in minutes between measurements, where zero implies a congruent measurement.

Figure 2
Simultaneity for observations of the role of clouds in climate and of the biogeoc hemical dynamics of trace gases based on the PAP analysis.

Biogeochemical Dynamics: Fluxes of Trace Species

The major challenge in developing a measurement system for remote sensing of the biogeochemical dynamics of trace gases, such as carbon dioxide, is to observe biological activity both on the land and in the oceans. The ocean is a dark target compared with the land, so that ocean-observing instruments require higher sensitivity. The PAP points out that the difference is particularly important in the near infrared, where precise MISR measurements must be made before the influence of aerosols on signals in the visible portion of the spectrum can be determined. Another complicating factor in making ocean color observations, indicative of biological activity in the surface layer, is the requirement that sunlight reflected from the water surface be avoided, which calls for a sensor that can tilt away from the vertical (i.e., the nadir).

The spectral coverage of MODIS-N provides data on land vegetation on a regional scale; similar data on a highly localized scale are obtained from HIRIS; MODIS-T provides ocean "color"; aerosol properties are measured by MISR; sea state and winds are obtained from STIKSCAT; and ocean circulation is derived from ALT.

Based on the need for spatial and temporal coverage, the PAP argues that MODIS-N, MODIS-T, and MISR should fly together. Although MODIS-N and MODIS-T view along very different tracks, the PAP concludes that the measurements should be taken simultaneously so that the ozone absorbance of MODIS-T can be corrected by the MODIS-N measurement. Further, the detailed high-resolution data obtained by HIRIS, on a spatial scale where human influences can be observed, must be related to the low-resolution MODIS-N data if global inferences are to be drawn. According to the PAP, the two instruments should therefore view the same scene at the same time. The MODIS sensors form couples with AIRS and AMSU in surface emissivity studies and in deriving ozone concentrations to connect MODIS and HIRIS visible channels. The PAP also concludes that ALT and STIKSCAT should fly with MODIS-T, but that observations in close sequence may be sufficient in this case.

Based on the PAP analysis (which is more extensive than the summary above) and our own discussions, we tabulated the requirements for simultaneity to support the study of trace species fluxes (see the lower left side of Figure 2). All instruments listed in the figure, except ALT, STIKSCAT, and EOSP, are currently part of the baseline payload for the EOS-A platform.

Based on these two research objectives, the PAP concludes that the following instruments should be flown on the same spacecraft: AIRS, AMSU, CERES-IN, EOSP, HIMSS, MISR, MODIS-N, MODIS-T, and HIRIS. This complement of research instruments, with the support instruments for communications and positioning (e.g., COMM and GGI), if selected for flight, would constitute a payload comparable to that envisaged for EOS-A.

We are not aware of any similar discussion of the currently proposed payload for the science objectives of the EOS-B satellite, although the positioning instruments, and perhaps others, may require some coordination to correct for atmospheric water vapor. The scientific objectives of that series and the set of instruments planned for it are directed at the chemistry of the atmosphere, the dynamics of its upper reaches, atmosphere-ocean interactions, and solid earth processes. Documentation exists for simultaneous measurements for individual pairs or sets of a few instruments. But neither the scientific investigations nor the measurements appear to demand the same considerations of simultaneity as those for EOS-A. In principle, the

EOS-B investigations could be done by a suite of smaller satellites. Arguments presented by NASA for a large platform for the proposed EOS-B instruments are based on engineering and systems considerations rather than on scientific objectives.

DOCUMENTATION

While there are a considerable number of well documented studies that provide general scientific arguments for measuring a variety of environmental parameters at the same time, there is little documentation linking the specific research objectives and the need for simultaneous measurements on EOS. No single peer-reviewed document or set of documents was available to which we could turn to find arguments for or against simultaneity among individual space-based measurements. Specific scientific arguments for simultaneity ("congruent," "simultaneous," or "close sequential") are contained largely in working documents, often in the draft stage. These include a detailed analysis of facility-class instruments, a detailed analysis of PI instruments, a briefing on NASA's "Science Plan" for EOS, and two draft letter reports to NASA from the Payload Advisory Panel of the EOS Investigators Working Group. The analyses of the instruments contain a wealth of detailed arguments for simultaneous measurements related to individual scientific objectives. Individually, many are convincing, but they are not integrated in the analyses. The PAP's draft letter reports integrate some of the arguments.

Our assessment of the quality of the available documentation is shown in Figure 3. Notwithstanding the lack of an overall analysis, we found adequate information in these working documents to construct a logical, scientific argument for congruent and simultaneous measurements for a certain set of parameters, and thus a certain set of instruments. Nonetheless, because the simultaneity arguments are central to the scientific success of the mission, it is essential that they be carefully described and made available for peer review. We therefore recommend that NASA prepare formal documentation that collects the scientific, measurement physics, and other arguments for simultaneity into one or a small number of documents to provide the traceability from the scientific need to the system design and guidance for the development and operation of the program over its lifetime. The document should be updated periodically to maintain that traceability as the configurations and payloads evolve.

	Available Documentation	Strength of Argument
Scientific (Processes)	Fragmentary in working documents	Good general arguments in a series of consensus reports; specifics in the draft PAP letters.
Physics	Fragmentary and in working documents	Strong in key scientific areas and examples.
Systems	Well developed	Very strong, but relies on physics or scientific argument as a basis.
Data Management	None identified	Potentially strong.

FIGURE 3
Summary assessment of arguments for a large platform for research on the role of clouds in climate and on the fluxes of trace gases.

7

EOS Platforms

Depending on the outcome of the question of simultaneity, are the EOS platforms, as currently configured, the optimal means for collecting data, or are there better alternatives that are more cost effective or timely? These alternatives could include, for example, smaller multiple platforms flying in formation or additional near-term precursor missions that are capable of flying subsets or preliminary versions of EOS instruments.

As discussed in Chapter 6, scientific arguments for simultaneous measurements have been developed by NASA for two specific research areas: the role of clouds in climate and the fluxes of the trace gases. With regard to these two cases, we conclude that the number of instruments that must fly together requires at least one large satellite. Dividing the proposed instruments for these measurements among several smaller satellites and flying them in close formation is technically feasible, but the smallest coherent set of instruments for one of the smaller satellites is still sufficiently large to require a launch vehicle larger than the Delta rocket.

The scientific requirements for continuity in data sets has led the community of researchers and NASA to plan for a long time-series of measurements. EOS plans call for a 15-year record of observations using series of identical satellites, each with a 5-year lifetime, for each set of measurements. Measurements to carry out the USGCRP emphasis on the role of clouds and the fluxes of trace gases, for example, are planned for a series of large spacecraft called the EOS-A series. It seems likely that scientific understanding and technical capabilities will change during the course of the EOS program. Accordingly, although continuity of specific data sets will be an important consideration, it may also be desirable to alter the instruments or the platforms, or both, at some time in the future. NASA has incorporated the design feature of common interfaces into the EOS program. This feature should make changing instruments easier than on many past missions. There is, however, no current plan for incorporating new understanding, concepts, or technology into EOS as they evolve during the life of the EOS program.

Scientific arguments for simultaneity in terms of the research objectives of the second proposed, large EOS-B satellite have not been developed, and it appears that these objectives could be achieved with a number of smaller, independent satellites. NASA's current assessment of comparative costs as presented to us, suggests that flying the projected EOS-B instruments on a large platform is the least expensive option, although the differences in cost among some alternative configurations appear to be relatively small. In principle, the science investigations proposed for COS-B could be done by a suite of smaller satellites. Since a number of the instruments do not require extensive development, these could perhaps be launched sooner.

Significant opportunities exist for gathering key global change data though a number of U.S. and foreign research and operational satellite missions, including the proposed Earth Probes series, prior to the scheduled first launch of EOS in 1998. Some of the EOS instruments are intended to continue monitoring certain environmental parameters so that the precursor missions that fly similar instruments will be prerequisites, not substitutes. Interim missions, including UARS, TOPEX, and the currently proposed missions in the Earth Probes series are intended to gather data that are essential for the USGCRP. It is our view that if budget constraints arise, it would be preferable to delay the the launch of EOS rather than to forego or diminish the effectiveness of these near-term projects. (See the section below on Precursors, Small Missions, Earth Probes, and Operational Systems.)

ENGINEERING CONSIDERATIONS

Four alternative configurations of satellites to carry EOS instruments have been analyzed to date by NASA: the baseline mission comprising two large satellites, EOS-A and EOS-B, on identical platforms; a mix of one large satellite and three satellites of intermediate size; six intermediate satellites; and 12 small satellites. Each satellite would be designed to last five years and would be replicated twice, for a net mission of 15 years. The large satellites would be flown on the Titan-IV launch vehicle, the intermediate ones would be sized to fly on the Atlas-IIAS, and the small payloads could be launched on Delta-II rockets. The NASA analyses do not account for the potential that some sets of satellites would have to fly in close formation to achieve the desired degree of simultaneity.

Launch Vehicles

Space missions are constrained by the availabilities and capabilities of the launch vehicles available for the purpose. NASA, in its analysis, considered a large number of factors, including cost, mass, power, data rate, launch vehicle, the ability of the launch option to satisfy the mission requirements, the number of spacecraft required, launch schedule, production schedule, operational complexity, data processing requirements, ability to fit the instruments on existing spacecraft, and direct data downlink and broadcast requirements.

The NASA analysis is constrained in two ways. First, there is currently no planned Atlas launch capability for the Western Test Range. As a consequence, the costs of a launch pad and the ground support crews would have to be provided, adding to the overall cost of any program that planned to use such a capability. It is not clear whether the launch rate would justify maintaining the crews at the Western Test Range or transferring them from the Eastern Test Range on demand.

Second, the Delta option could not accommodate some of the larger instruments, such as HIRIS, ITIR, MLS, GLRS, and HIMSS, without changes in the instruments or the spacecraft. Based on the NASA analysis, the all-Delta scenario seems to us to be technically unrealistic.

Thus from consideration of the capabilities of the respective launch vehicles, there are several discrete "levels" of capability rather that a continuum. If, as discussed above, the scientific investigations or the measurement capabilities to support them require the simultaneous flight of sets of instruments, the designers are led at this time toward the large spacecraft as the "optimum" configuration. Nonetheless, we believe it would be prudent at this time to continue to consider a mixed launch vehicle scenario so that the scientific return of instruments currently designated for EOS-B can be increased or achieved sooner. The option should not be eliminated solely on the basis of consideration of the launch vehicles.

The Platform Systems

There is no inherent risk in a structure of the size of the EOS-A satellite. The major development risk lies in the subsystems and complex interactions inherent in integrating and flying many instruments together.

Systems interactions in cooling, viewing angles, data management, mechanical and electronic noise, and other factors have complicated multiple instrument space missions in the past. These are engineering challenges that can usually be identified and solved. Nonetheless, there is always a risk that some interaction will not be anticipated and mitigated in advance. This is not an issue that we could deal with in our deliberations, and it is in any case never conclusively solved at this stage in the development of a space mission.

The data system will require tape recorders that are a significant extrapolation from current technology. While we accept the assertion that the extrapolation is straightforward, past experience suggests that extra tape drives should be supplied where they will be critical to the operation of the mission. The experience in the NOAA TIROS series has been that half of the tape drives fail on orbit before the end of the mission and usually early in the mission. Providing extra tape decks, which is NASA's current plan, will require extra space on the spacecraft, but it can be supplied with the larger platform.

Similar arguments can be made for most of the subsystems. In general, the larger platform has greater capability to provide backup or redundancy. Extra weight or volume capacity on the part of the launch system further allows for the use of cheaper or less exotic materials and simpler designs, and makes possible arrangements for passive cooling of several instruments and unobstructed views of Earth by several instruments in relatively simple ways.

The large platform also allows NASA to consider a direct downlink for data as another service for users and as a backup for telecommunication via the TDRSS, which is the baseline configuration. The user community has derived much benefit from the use of low-rate, real-time direct broadcast from the current meteorological satellites. The capability would be advantageous for EOS instruments, and it is currently planned for the EOS-A and EOS-B satellites.

CONTINUITY AND RELIABILITY

The USGCRP gives high priority to the establishment of an integrated, comprehensive, long-term program of documenting the Earth system on a global scale. The EOS will be a key component of that overall program, which will include surface-based measurements as well. It is essential that EOS be both comprehensive in its coverage of parameters in space and time and that it provide for continuity of calibrated data for the most critical of them.

Data continuity is particularly important when the required information is used both to establish a baseline about global change and to monitor change as it occurs. If the critical instrument is not in place when major events occur, such as an El Niño or a major volcanic eruption, then opportunities to document and learn about the Earth system will have been lost. Furthermore, identifying trends in highly varying data is always compromised when a portion of the time series is missing. If data on clouds or the radiative balance were missing for either extreme of the solar cycle, for example, understanding of the related phenomena would be severely degraded. Loss of continuity also severely compromises the warning capability of the observing system. Consequently, the reliability of EOS data is important to the USGCRP. Considering the potential for long-term drift in instruments, the issue of calibration warrants particular attention.

In our view, NASA has established reasonable criteria for the needed reliability for the scientific mission. For example, the large spacecraft platform is being designed to have a 75 percent probability of full capabilities for its expected operating life of 5 years, as well as a 75 percent probability of having 80 percent of its design power capability at the end of 7.5 years. NASA's current requirement for the instruments is a probability of at least 85 percent that they will be working satisfactorily at the end of 5 years, while for certain measurements of the facility instruments the requirement is at least 90 percent. NASA's preliminary analyses indicate that these probabilities are within reach and can be met.

Continuity failures are more difficult to quantify. Three types of failures can occur, threatening the continuity of measurement: first, the launch vehicle can fail. NASA's plan for this contingency is to provide a spare platform and set of instruments that would be available for launch as soon as possible after the failure. In the interim, the lifetime of a platform already operating in orbit could be extended until such time as the replacement is launched. The longer the lifetime of an operational platform is extended, the greater will be the likelihood that the continuity of some data streams will be lost. If a failure occurs during the launch of the first platform in either of its proposed series, NASA projects that the delay for the beginning of that series would be 2.5 years. An interruption in the time series of this magnitude would seriously disrupt USGCRP research objectives.

The second type of failure is of the platform itself, once it is in orbit. Platform systems, such as the attitude control system, data management system, power supply, and telecommunications system, are essential to the operation of all instruments. The least reliable element of the platform infrastructure is widely regarded to be the tape recorders, six of which are currently planned to assure that at least two are always operational. The spare platform and set of instruments is intended to provide backup in the event of a platform failure, but it is clear that continuity in some of the data records would be lost. An interval would be necessary to determine the cause of the failure, take corrective actions as required, and launch a replacement platform, even if the platform, instruments, and launch vehicle were available at the time of failure.

The third type of failure is of an instrument. Most of the instruments have a technical heritage in devices that have already been flown. Nonetheless, several proposed instruments require significant advances in technology. NASA currently estimates that development of the most complex instruments on EOS-A will take between 42 and 60 months, with some technological risk entailed.

One way to help assure the continuity of critical measurements in the event of an instrument failure is to place redundant sensors on the platform. The approach would, however, inevitably result in a reduction of the size and scientific scope of the complement of sensors on the platform.

Another approach, applicable to either partial or catastrophic failures, would be to provide so-called "hot spares" for critical instruments, spare instruments, and launch vehicles ready to go with minimum delay. This approach also has disadvantages: it is costly, and program managers are likely to want to determine the cause of failure and take corrective actions before launching a spare, increasing the interval of discontinuity of the data. NASA estimates the cost of providing for a typical hot spare to be in the $250M to $350M range. Further, depending on the instrument and the acceptable degree of simultaneity with other measurements, close formation flying may be required. If the lost instrument were to be in a set requiring congruent measurements, the hot spare could not restore the relationship.

A third approach, which might also apply in the event that an instrument is not ready at the scheduled time for launching, would be to use existing instruments on the platform to provide backup. In a working document entitled *EOS Instrument Standard Data Products*, NASA is assembling backup strategies for each data product in the event of loss of an instrument or channel in an instrument. The products being examined include such parameters as biomass characteristics, broken ice distribution, carbon monoxide profiles, temperature profiles, ice sheet height, and many others. Backup products would be degraded from the originals but would be constructed from channels of other instruments to give crude but workable data for gap-filling purposes. This approach and other aspects of contingency planning are still under development by NASA.

Finally, given the extensive remote sensing capabilities and plans of other nations, full coordination of EOS with the foreign programs could contribute to maintaining critical redundancies. NASA should place high priority on such coordination.

Any approach to providing for the contingency of instrument failure will entail balancing costs, technical capabilities, and other considerations with the scientific goals of the program. The question of the reliability and continuity of data is central to the mission, so that careful contingency planning is important. We conclude that an important first action is to identify the mission-critical sensors for which contingency plans have highest priority. NASA considers the MODIS-N and -T as the "mission critical" instruments for the first platform series, so much so that the agency is prepared to delay the mission until these instruments are ready. We agree with this assignment of priority, particularly since the MODIS instruments are part of a suite that will provide significant benefits from simultaneous measurement and which serve the highest priority scientific objectives. A careful analysis needs to be done to determine whether there are others. A related question is the need for companion instruments with any such mission-critical instruments.

After the mission-critical sensors have been identified, the next step is to identify ways in which an EOS instrument failure could be covered, and with what degradation to the science, with other instruments that are already flying. For example, the following types of questions need answers for each standard data product. To what extent can a data gap in MODIS be met with data from AVHRR, Landsat, and SPOT? How well can a gap in observations by AIRS be met with data from HIRS and AMSU? How well will ALT coverage be continued with ERS-2, U.S. Navy altimeters, and others? What will be the alternative SAR coverage with the Canadian, European, and Japanese missions?

In summary, NASA's current science strategy does not fully address the issue of continuity of key data sets throughout the 15-year lifetime of the mission. We conclude that NASA needs a contingency plan for instrument failures. Changing scientific priorities may lead to different designations of "mission-critical" instruments. The plan could distinguish among instruments, but the scientific requirement for simultaneous, congruent measurements, which provide the rationale for a large platform for the highest priority science objectives, should be the guiding principle of the plan. The panel's suggestion that the instruments for EOS-B could be flown on a number of smaller satellites could also be used to help address continuity and backup issues. The data continuity issue is so important that it deserves continuing careful financial analysis and consideration.

NASA's analysis indicates that the large platform approach gives the better overall reliability. Because this analysis is based necessarily at this time on design criteria rather than actual designs, we find the preliminary analysis to be less than conclusive. Nevertheless, the NASA analysis adds another argument to those already mustered in support of the large spacecraft for the two highest research priorities.

COSTS

At this time, NASA's cost estimates are not sufficiently precise to support a conclusion about whether a configuration of one large platform with several smaller complementary spacecraft is more or less costly than the proposed two large platforms. The NASA cost estimate for an observing system with a comparable payload that consists only of small spacecraft, however, indicates that such a configuration would be roughly 50 percent more expensive than either of the other two options.

The relative costs for four mission configurations as analyzed by NASA are given in Figure 4. The analyses are normalized to the baseline concept for two platform series. For each case, both an optimistic and a pessimistic estimate are given. The analyses are based on NASA cost models and the assumption that the same total set of instruments would be flown in each case. The assumption is probably not valid. The costs associated with contingency plans, which may differ among the configurations, are not included either.

Aside from the totals, several features of these cost analyses are striking. First, the vehicle costs in each case are a small fraction of the total system costs.

At some number of satellites in orbit, which happens to just about coincide with the number in a mixed fleet, an additional TDRSS is needed. This is driven by the need for committed access to a high data rate channel for several of the satellites. With the Atlas and mixed ELV scenarios, additional costs will have to be met to sustain a dedicated launch capability at the Western Test Range.

Obviously, the costs for integration and testing increase with the number of spacecraft. While the relationship is not linear, since the smaller spacecraft are simpler, there is real increase just from the numbers. This is especially true in the case of the Delta launch scenario where each spacecraft may have to be individually designed for each instrument to fit within the shroud.

The costs of operations will also grow as the number of satellites and the number of orbits are increased. Further, in the area of science, atmospheric corrections or co-location of images will require increasingly complex algorithms as simultaneity is lost and resulting costs increase.

Because the precision of the NASA estimates is not high, there is little to choose in terms of cost between the baseline case, the mixed case, and the lesser assessment of the all-Altas configuration. Questions about the costs of establishing a polar orbit launch capability for Atlas-IIAS rockets and providing the requisite ground support personnel suggest that the differences in costs among the respective configurations may be larger than the analysis indicates. Nonetheless, since the differences between the mixed scenario and the baseline are not large, we recommend that NASA continue studies now under way to optimize the scientific return from the instruments carried in NASA's strawman payload for EOS-B.

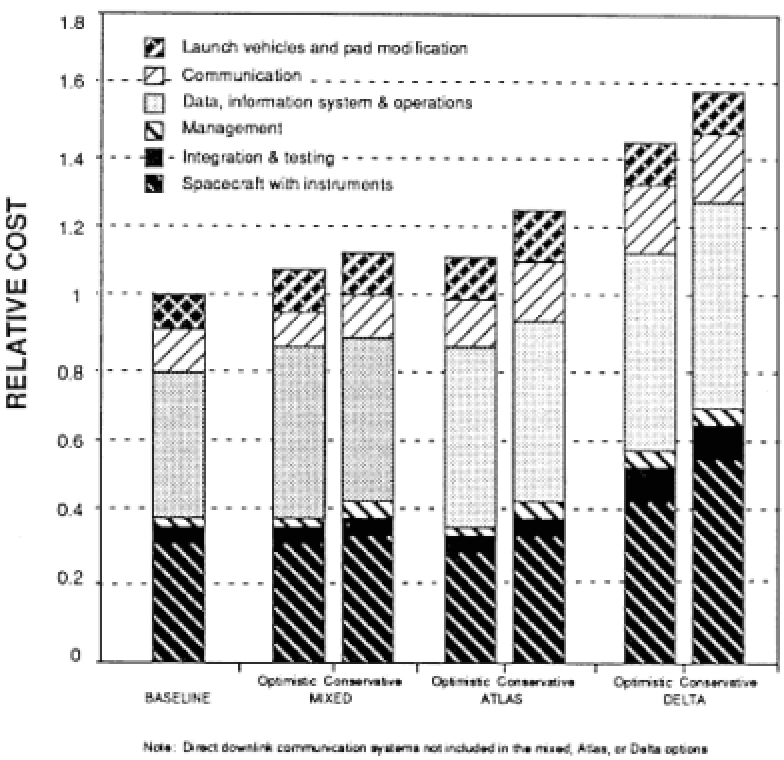


Figure 4
NASA estimates of relative costs of alternative mission configurations with ide ntical
instrument payloads. SOURCE: C. J. Scolese, NASA Goddard Space Flight Ce nter, April, 1990.

PRECURSORS, SMALL MISSIONS, EARTH PROBES, AND OPERATIONAL SYSTEMS

The first of the EOS platforms is scheduled to be launched in 1998. In the interim, significant opportunities exist for gathering key global change data in precursor missions in the Earth Probes series. Also, the agency plans to develop the EOSDIS as early as possible in order to make available to the research community other historical data sets and data streams from on-going operational satellites that can be used to experiment with prototypes of the data and information system in evaluating management concepts.

The scientific justification for several precursor missions, including Earth Probes, and the use of data from existing operational systems (e.g. Landsat and the meteorological satellites) was discussed earlier in Chapter 5.

Because Earth Probes are planned as smaller satellites with shorter development times, they have considerable potential for providing high-priority precursor measurements to EOS. They also can advance the time in which some of the measurements critical to understanding global change could be made (see the SSB/CES report, *Strategy for Earth Explorers in Global Earth Sciences*, 1988). An important concern in the near term is the discontinuity of key measurements such as global stratospheric ozone levels, the Earth's radiation budget, ocean topography and winds, and the biological productivity of the oceans, made by satellite missions launched in the 1980s. Certain missions proposed for the Earth Probes line could provide opportunities for extending those measurements until acquisition of the data sets is assumed by the EOS spacecraft. However, there is no Earth Probe mission proposed to fill the gap in Earth radiation budget measurements, as mentioned above. Certain other Earth Probes missions could also provide information on parameters not measured before on a global scale, e.g., the Earth's gravitational field and tropical rainfall.

There are other opportunities for early flight and for providing continuity of currently important measurements that do not seem to be as well exploited as they might be. These are flights of opportunity on already planned missions. Satellite series like the NOAA polar orbiters and the satellites of other nations can provide opportunities for modest instruments. The flight of the SBUV instrument on the NOAA polar orbiting series and the planned flight of the TOMS instrument on a Soviet meteorological spacecraft are instructive examples.

Several important existing measurement capabilities are candidates for such "piggy-back" flight. They include flying another ERBE on the NOAA series, an active cavity radiometer on almost any satellite series, and an ocean color instrument. The contributions of these measurements to the objectives of the USGCRP are described in Chapter 5.

In addition to possibilities for precursor or interim flight of selected instruments, some measurements could be better made, or must be made from other orbits. For instance, biological processes and radiation studies related to cloud motion require sampling at various times of day, which cannot be made solely from sun synchronous polar-orbiting spacecraft such as EOS. To the extent that these measurements are critical to achieving the objectives of global change research, the Earth Probe line can provide a flexible mechanism for such observations from more appropriate orbits. During the EOS era, Earth Probe missions will also be essential in complementing the EOS measurements by flying instruments that may be incompatible with the design and orbit of EOS platforms. It is expected that the Earth Probes will be augmented by foreign spacecraft, some of which could provide flight opportunities for U.S. instruments. For instance, discussions are currently under way to position the Japanese spacecraft contribution to EOS in a lower inclination orbit. A plan is needed to determine how to coordinate such possibilities with the USGCRP.

Of the several instruments that can be better flown in a different orbit, we believe that the Synthetic Aperture Radar is of prime importance. If its technological development is successful it will supply two quantitive measurements unavailable on a global synoptic scale in any other manner. These are soil moisture and an estimate of biomass in a standing plant canopy. Both of these measurements are important for the two top priority scientific areas, i.e., the hydrologic cycle and fluxes of atmospheric gases. The SAR should be considered for inclusion in the EOS program as a free flier as soon as possible.

Existing U.S. operational systems supply both interim data and a continuing contribution to global change research. They include the NOAA polar orbiting and geostationary meteorological satellites, the Defense Meteorological Satellite Program (DMSP), and the Landsat system. Many scientific studies proposed for EOS assume the continuation of these measurements. For instance, the top priority study area—the role of clouds in the hydrologic cycle—assumes the continued measurement and mapping of clouds by the meteorological spacecraft. The second priority area, fluxes of atmospheric gases, assumes the continued global mapping capability of a Landsat system intermediate in capability between MODIS and HIRIS.

NOAA and NASA are jointly planning for flight of atmospheric sounders and for a common interface for a number of the instruments, an approach that we endorse. Further, the European partners in EOS are planning to fly a polar orbiting platform with a morning crossing of the equator to cover the requirement for operational weather data, again with a common interface. This continuing use of operational data and integration of the hardware approaches will benefit scientific investigations of the future.

These research and operational missions are complementary to, not replacements for, the main EOS missions. They will improve the scientific return of the space-based Earth observing program, and they can help to ensure continuity of key observations for the next decade or longer. Some, such as Sea WiFS, are important for the success of planned international field programs that will improve understanding of global change.

8

The EOS Data and Information System

Does the proposed EOS Data and Information System (EOSDIS) represent the appropriate approach to support this long-term data collection and modeling effort?

The preeminent challenge to global change research is the synthesis of diverse types of information from different sources. EOSDIS is a pioneering effort in this regard: the intended scope of the system far exceeds that of any existing civilian data management system. Nonetheless, relevant experience for developing some aspects of EOSDIS exists in pilot data programs in NASA and in the data programs of other disciplines and agencies. If EOSDIS succeeds, it will be both a key ingredient in the success of the U.S. Global Change Research Program (USGCRP) and a substantial contribution to the field of data management. On the other hand, there is no operational paradigm for the effective management and dissemination of large scientific datasets under which data can be obtained readily and quickly for analysis and research.

Nor is there any formula for success in such an endeavor. The EOS instruments will be examples of advanced scientific and engineering concepts, producing many simultaneous data sets, each with large amounts of data. Significant advances in data management will be required so that these data will be readily available and useful for modeling global change.

To prepare for this challenge, NASA proposes to commit a major fraction of the EOS budget to the Earth-based component, including EOSDIS. NASA should be commended for its early recognition of the importance of the EOS Data and Information System (EOSDIS) to the success of EOS and the USGCRP. This importance is best summarized in the words of the EOS Science Steering Committee:

> The key to the EOS concept and to its ultimate success in meeting the needs of the Earth science community is the data and information system. This system must be the foundation upon which the rest of the mission is built; it will be the means by which all EOS results are collected and communicated. [pp 25–27 *From Pattern to Process: The Strategy of the Earth Observing System*]

We agree that investing in the early development of EOSDIS is appropriate and necessary for the long-term success of the EOS data collection, management, and modeling effort. Some previous NASA missions have suffered from depleted budgets before the data processing and scientific analysis phases were done, resulting in a poor scientific payoff. The EOSDIS program is beginning with a healthy commitment to data management and analysis.

Investment does not guarantee success, however. The EOS program will be large and complex, and many potential pitfalls will be faced in the course of its implementation. While the importance and challenge of EOSDIS are understood, it is not equally clear that the route to achieving such a system and the resources and advance planning required to implement, maintain, and evolve it are fully appreciated. The management of very large databases with provisions for indexing, browsing, visualization, and other capabilities is a research issue. Current understanding of how to meet this challenge is not mature. A program of research is needed to guide the evolution of the proposed data management capabilities.

CHARACTERISTICS OF THE SYSTEM

EOSDIS will support a variety of scientific activities. According to NASA plans, its major functions are:

- mission planning, scheduling, and control;
- instrument planning, scheduling, and control;
- effective resource management;
- communications;
- computational facilities to support research;
- production of standard and specialized data products; and
- archiving and distribution of data and research results.

NASA currently plans to have EOSDIS operational well before the launch of the first EOS spacecraft. The processing, archiving, and distribution of data are to be functional by 1994. Prior to the first launch, EOSDIS plans are to exploit currently available data, enhance the data acquisition and processing capabilities for ongoing missions, and correct some long-standing deficiencies in the access to data. Development is to begin immediately, building on the existing infrastructure.

NASA plans call for a network architecture that is open and distributed, capable of evolving with advances in computing and networking. In the terms used by NASA, "EOSDIS must adhere to a flexible, distributed, portable, evolutionary design and operate prototypes in a changing experimental environment." In our view, this is the right approach, but these goals are easier to state than to accomplish. The challenge of achieving them must not be underestimated.

In the development of EOSDIS, NASA has had the benefit of interactions with other federal agencies and the external scientific community. In the former case, the Interagency Working Group on Data Management for Global Change has been a forum for discussing data, distribution, format, access, cataloging, and related topics affecting interagency management of data and their accessibility. Agencies participating include NASA, NOAA, USGS, DOD, DOE, and EPA. In addition, the EOS Investigators Working Group has organized a Science Advisory Panel for EOSDIS that is charged to represent the scientific community associated with EOS in advising NASA on matters related to EOS data production and scientific interfaces.

Evolution

The computer industry has experienced increasingly rapid technological evolution in both components and architectures. EOSDIS must be flexible enough to take advantage of inevitable advances in hardware and software capabilities, particularly in areas such as high-performance computing, data storage media, disk controllers, networking, and data base management. How hardware and software technologies will change over the next 25 years cannot be predicted, and traditional contract specifications for EOSDIS hardware and software written today cannot remain unchanged over the long term.

Consequently, NASA should not attempt to define total system specifications at the outset and then assume that they will not be altered throughout the remainder of the program. First, the evolutionary approach should rely heavily on experiments with prototype elements and include continuing interactions with and testing by members of the research community. Second, EOSDIS should have a system architecture sufficiently flexible to accommodate changes and to implement them in an evolutionary manner.

Third, priorities for EOSDIS should be driven and determined by the research, monitoring, and modeling that will have to be carried out in answering fundamental questions about global change. When modifications to original specifications must be made for budgetary, performance, or other reasons, the global change research community should have a major role in advising on priorities. A broad scientific input will assure that EOSDIS priorities are based on research requirements.

Diversity of Data and Information

The success of EOSDIS, like that of the USGCRP, will ultimately be judged on scientific results rather than by how many bits can be processed for the fewest dollars. To achieve the objectives of the USGCRP, the system must include datasets from a diverse array of space-and ground-based sources, which poses significant challenges to its design.

Data Diversity

The demands of the USGCRP require that data and information from EOS be merged with datasets from a variety of disciplines and sources. EOSDIS must be able to cope with a wide spectrum of data and information types. It cannot be focused simply on the data needs of NASA, or even those of the United States. EOSDIS must provide the capability for accessing and interpreting data and information from many agencies domestically and from a number of other countries.

Many ancillary datasets, which will be needed to exploit the scientific value of EOS data properly, are likely to be collected and held by agencies other than NASA, such as NOAA and USGS. The USGCRP recognizes this need, as do the participating agencies. In particular, NASA, NOAA, NSF and the USGS, as agencies prominent in the collection and dissemination of data, have a special responsibility for working together to assure greatest accessibility to all data and information relevant to understanding global change. Some NOAA, NSF, and USGS centers are already primary repositories of geoscience data, and they have substantial experience and expertise in data archiving that could be of advantage to EOSDIS. The objective should be an integrated national system for processing, distributing, archiving, and retrieving data and information about global change.

Human Interactions

While the needs for data and information by the human interactions component are not yet well defined, the data and information involved with this research will be sufficiently different from those customarily collected and archived in earth remote sensing missions that special attention should be paid to this field. As discussed in Chapter 5, NASA has an important role for ensuring that EOSDIS is responsive to these requirements as they evolve. We therefore encourage NASA to work with others, including both the natural and social sciences research communities, to assure that EOSDIS will contain data useful for human interactions research.

Conversely, EOSDIS could also provide the means for physical scientists to obtain those human interaction datasets that might enhance their scientific studies or that might help define the relevance of their research to sociological, political, and industrial decisions.

A Distributed System

In a project of this scope, there are inevitably divergent views on the proper balance between distributed and centralized responsibilities for data management. The appropriate balance can only be determined through experimentation and experience. A distributed system should be used to take advantage of scientific expertise as well as computational facilities. This basic requirement argues strongly against the development of a centralized system.

Though distributed, EOSDIS should appear to users as a single integrated system. All users want "one-stop shopping" for their data. The technical means are available to build a system that is distributed nationally and even internationally so that the user needs only a single point of entry to access all the data. EOSDIS planning within NASA seems to be heading in this direction.

For example, NASA proposes to establish a network of EOSDIS Distributed Active Archive Centers (DAACs). Seven have been selected to date. Each DAAC would carry out routine production, distribution, and archiving of EOS data and data products. In addition, NASA has proposed that a number of Affiliated DAACs be located "outside of the critical path for EOSDIS." Among other functions, these Affiliated DAACs would provide access to important non-EOS data and services.

While planning documents apparently are still in a state of flux, we strongly endorse the concept of distributed archive centers charged with storing data and data products and making them available to users. We are concerned, however, about two important issues: criteria for selection of the centers and relationships between the DAACs and the Affiliated DAACs.

We were unable to obtain clear descriptions of the criteria for the selection of DAACs or of the selection process. The criteria should be readily identifiable and publicly stated. It might be desirable for a joint working group of NASA personnel and extramural scientists to define the operational and scientific criteria.

The broader questions are: What is the total range of responsibilities that can be defined for dealing with data issues before and during the EOS missions? Which activities should be handled at DAACs, which elsewhere, and how are sites for all activities to be selected?

Of the seven DAACs named thus far, five are at NASA centers.

NASA's stated objective is to build a national distributed data and information system whose principal aim is scientific understanding of global change. We believe that such a system is likely to benefit from involvement by centers outside NASA, particularly in the academic community.

We recognize that some NASA centers have extensive experience on which to build EOSDIS. It is natural that some will become critical EOSDIS centers. Nevertheless, we believe it is important to establish an objective process that includes peer review before DAACs are named and funded. Such a procedure would optimize the effectiveness of a distributed EOSDIS consistent with the priorities of the USGCRP.

Though some centers outside NASA have been identified in EOSDIS planning documents as Affiliated DAACs, their role and status in the EOS program have not been well established. It is also unclear whether they will receive adequate support. In summary, the entire matter of the DAACs needs study and clarification.

NASA'S DATA POLICY

NASA policy is that all data collected by the EOS program will be archived in EOSDIS, and all EOSDIS data will be made available to the research community at the incremental cost of distribution. EOS data and information will be available to all users; the only distinction among users will involve cost. There is to be no period of exclusive access for any group, including the EOS principal investigators. Where EOS sensors make site-specific observations, EOS will be an "acquire-on-demand" system as opposed to a "process-on-demand" system. The data system is to provide unprecedented ease of access to observations. NASA hopes to have a common data policy for the entire international suite of data.

According to NASA's EOSDIS policy, users who agree to place the results of their investigations in the open literature will pay only the nominal incremental cost of reproducing and delivering the data requested. In exchange for access at low cost, these users must agree, through the stipulations of a standard "Research Agreement," to make available to the research community the derived data, algorithms, and models at the time of acceptance for publication. Low cost data are to be used only for the researcher's bonafide research purposes. Data may be copied and shared among other researchers provided that they are covered by a Research Agreement or that the researcher who obtained the data is willing to take responsibility for compliance. Commercial users of EOSDIS will be charged market prices through an intermediate vendor.

We welcome NASA's policy of open distribution for research of all EOSDIS data. Since the EOS program will be judged on its scientific results, maximizing the scientific use of the data is the optimal strategy.

Moreover, as a repository for an extensive range of data pertinent to global change, the success of the USGCRP also depends on the openness of EOSDIS.

A number of impediments to accessing the data are currently limiting the effective scientific use of various existing datasets for global change research. In this regard, we would call attention to two impediments—related to data management policies and insufficient resources—that require immediate attention if EOSDIS is to be successful.

Landsat and Other Commercialized Datasets

Current policies that govern the use, distribution, and cost of the Landsat and SPOT data make it difficult for the research community to take advantage of this resource. When purchased from the commercial remote sensing industry, the data are generally too expensive for most research purposes.

Current legislation intended to protect the commercialization of Landsat remote sensing activities unfortunately prevents the inclusion of these important data in EOSDIS unless the government purchases the data for that purpose. In our view, Landsat data are sufficiently important to global change research that means should be found to include them in EOSDIS, whether by revising the Land Remote Sensing Commercialization Act, if necessary, or by paying (again) for the data.

We also believe that it is in the interest of international research to make all environmental data readily available to the global scientific community. Indeed, this is NASA's stated policy in regard to EOSDIS: scientists anywhere in the world with appropriate telecommunications equipment will have access to EOSDIS provided that they adopt the standard research agreement. Only by such a strategy will the usefulness of the data be maximized. Similarly, U.S. scientists should have access to relevant data in foreign archives, and it is important that other nations be encouraged to establish similar data policy assessments.

Preservation of Historic Datasets

Changes in technology and insufficient attention to maintenance of irreplaceable historical datasets currently in various archives threaten to limit their usefulness. In some cases, valuable data may be lost altogether.

For example, almost all the NOAA 1km AVHRR data obtained prior to 1986 have essentially become inaccessible because they are still stored in an outdated system. Early Landsat data at the USGS's EROS Data Center in Sioux Falls, South Dakota, and NOAA geosynchronous satellite data at the University of Wisconsin are at risk of being lost forever because their storage media are deteriorating. The success of global change research will depend in part on the availability of a long time series of measurements. The existing archived data are a most important resource in this regard. If lost, they are not replaceable.

The USGCRP recognizes the need to preserve historical data and includes some funds for the purpose in the FY 1991 budget. We underscore the urgency of moving all relevant data to more secure storage media and incorporating them into the EOSDIS as soon as possible.

RESEARCH AND PROTYPING NEEDS

Plans for EOSDIS emphasize that the system will maintain continuity with current data systems because the current data centers provide a heritage for the design and prototyping of EOSDIS. If this approach is to succeed, those involved with EOSDIS development and implementation must be committed to an evolutionary approach using system prototyping. We are concerned that this commitment has not yet taken hold, and it may be difficult to establish once a contract is written to procure design and implementation services. Contracts normally include precise specifications for deliverables, but in the case of EOSDIS a description of the system—and even its performance goals—is premature.

EOSDIS must be an evolving entity, even over the entire life of EOS; it is not a system that can be designed, implemented, and then left to function unaltered throughout the remainder of the EOS program. NASA appears to view EOSDIS as an evolving entity, but research will be required to provide the basis for implementing EOSDIS.

The proposed structure of EOSDIS, the various entities involved, and their interactions were evolving conceptually even during the brief period that we were conducting our review. We regard this as a healthy sign for the future of EOSDIS. To ensure that the evolution continues, there should be a coordinated plan that incorporates a deliberate program of data system research and prototype development.

Prototyping

In our view, the community of researchers, including those in the fields of high performance computing and data management, is not yet ready to start designing certain aspects of EOSDIS. In many areas prototyping efforts should be under way, with dedicated people directing them. A number of areas where work is needed are listed in Table 1 and discussed in Appendix C. The list is long, but it is difficult to shorten it because the community collectively has not yet reached the level where the magnitude of the problem is understood.

TABLE 1: Elements of EOSDIS Requiring Prototype Development

Data visualization and the user interface
Browsing capability
Data formats and media
Accessibility of data and information
Cataloging
Search and query capabilities
Model and data interaction
Metadata* and data structures
Data reduction algorithms
Networking

* Metadata is defined in Appendix C as information about data, such as documentation.

Questions still to be answered include how to get NASA, other agencies, the DAACs, contractors, and independent scientists and computer engineers working together in defining problem areas; analyzing requirements; and using the results to establish prototype approaches that are likely to be effective; creating designs; working together on interfaces, design, capabilities, and other aspects; bringing the creativity of complementary kinds of expertise together; and exploring alternative approaches that conserve available human and financial resources.

Prototyping should address the challenge of the immense size of EOS datasets, which will dwarf any previous experience. As part of the prototyping activity, some EOSDIS centers should be co-located with institutions with high-performance computing and global modeling capabilities. Such centers, which should have the capability for large temporary data repositories, could well be at research centers but not necessarily at EOSDIS DAACs. The high-performance computing capabilities required to effectively exploit EOS datasets are likely to greatly exceed current expectations. Because of its scale, EOSDIS is likely to break new ground in the use of computing technology in research.

Pathfinder Datasets

EOSDIS plans call for the creation of "Pathfinder Datasets" that will incorporate currently existing data important to global change studies. The data sets include derived data products, chosen on the basis of community consensus. The procedures will include the validation and archiving of derived products. Among the datasets under consideration are AVHRR, GOES, TOVS, and others from earlier satellite missions. The selection of the Pathfinder Datasets will be driven by global change science requirements.

We endorse this approach. There is a critical need that proto or pilot datasets be made available to the scientific community. To challenge the system effectively, such sets should cover a range of sizes typical of those to be produced by EOS instruments, for example, from less than half a terabit to significantly greater than a terabit.

INDEPENDENT SCIENTIFIC ADVICE

We strongly believe that cooperative and constructive interaction among scientists in the global change research community, on the one hand, and software design engineers and software implementation programmers, on the other, will be crucial to the success of EOSDIS.

In the business community, it would be unthinkable for a software firm to design a large package for management of bank records or airline reservations without steady interaction with users and corporate executives. The former can provide feedback on what works and what does not, and the latter on what the system priorities are. In a project like EOSDIS, individual scientists will be needed to work actively with the system as it develops and to provide feedback. A committee of scientists dedicated to the goals of USGCRP can provide an overview of the top priorities.

Experience gained from software development for serving the needs of scientific communities has pointed strongly to the same conclusion. Major software systems developed without steady involvement of users have generally been failures; those that maintained advisory committees of scientific users were almost guaranteed success (provided the design and programming expertise was present) because potential problems were caught in the design or early development.

To date, NASA has worked effectively with several committees that consist partly or wholly of scientists, and all indications are that this has been a positive and productive interaction. Such cooperation should continue throughout the development of EOSDIS, notwithstanding historical precedent and the fact that scientists and software engineers tend to speak different languages and sometimes have trouble communicating. We strongly emphasize the importance of maintaining a three-way structure in the evolution of EOSDIS, with NASA and other agencies involved in the USGCRP, research and instrument scientists, and the contractor(s) working together as equal partners. Excluding any of those three groups from being involved with software testing and decision making would be a major mistake.

In our view, the EOS Investigators' Science Advisory Panel for EOSDIS has successfully focused the concerns of a broader research community, and has articulated the specific requirements of scientific users in the context of the EOS mission and the USGCRP (see, for instance, the EOSDIS Science Advisory Panel's November 1989 report). EOSDIS planners have been responsive to the advice of the Science Advisory Panel, and as a result of its guidance a major redirection of EOSDIS design strategy has taken place in the last few months.

Because the implementation of EOSDIS poses significant, continuing challenges, we believe that EOSDIS must have an ongoing mechanism for acquiring independent advice from the user community. The EOSDIS Science Advisory Panel should be a long-term advisory element in the agency's planning and implementation process. It should include some scientists who are not EOS investigators but who are active in fields with the range of scientific disciplines involved in global change research as well as in research on data and information management. We therefore recommend that the Panel EOSDIS Science Advisory Panel continue to perform its function throughout the EOSDIS procurement, design, and development cycle to ensure that all the major scientific requirements are effectively met.

APPENDIXES

Appendix A

The Charge to the National Research Council

THE WHITE HOUSE

WASHINGTON

January 29, 1990

Dear ~~Dr. Press~~ Frank:

President Bush has made global environmental issues a major priority in this Administration. He has set in motion a comprehensive process designed to continue U.S. leadership on the issue of global change, including a major initiative focused on improving our understanding and predictive capabilities related to global change. Specifically, the FY 1991 budget requests $1034 million for the U.S. Global Change Research Program (USGCRP), an increase of 57 percent over the FY 1990 enacted level. A major element of this effort is a proposed new start for NASA's Earth Observing System (EOS). EOS is part of the Mission to Planet Earth concept announced by the President on July 20, 1989.

The FY 1991 USGCRP budget and research plan is the product of a major interagency planning effort coordinated by the Committee on Earth Sciences (CES). Many individual elements of the USGCRP have received extensive review by the scientific community. However, because of the importance and magnitude of this initiative, I believe it is critical that the entire global change research program be thoroughly reviewed, understood, and supported within the broader scientific community. It is, of course, important to the nation that we make the most effective use of our scientists, resources, and time in this key study of the global environment.

To this end, I would like to request that the National Research Council review the interagency USGCRP, as described in the President's FY 1991 budget, to ensure that this research effort represents a sound approach to reducing the scientific uncertainties associated with global change issues. In particular, I am requesting that the review address several specific issues regarding EOS, including the environmental parameters to be measured, the requirement for simultaneity of data collection, and the optimal configuration of the EOS platform and instruments. Unlike the general USGCRP review, I believe the EOS questions will require carefully selected representatives from both within and beyond the earth sciences research community.

It is important that the results of this review be available prior to the beginning of FY 1991 and the final development of the FY 1992 budget. This review is critical to the CES planning and implementation of the USGCRP. It is also important to OSTP and OMB in exercising their oversight responsibilities, and to the National Space Council, which plans to review the role of the USGCRP space components relative to national space policy.

Enclosed please find a proposed Terms of Reference for the review. Please let me know if this review is possible and what additional steps I might need to take to ensure its timely completion.

Sincerely yours,

Allan

D. Allan Bromley
Assistant to the President
for
Science and Technology

Attachment

Dr. Frank Press
President
National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

cc: The Honorable Robert Grady
The Honorable Lennard Fisk
The Honorable Mark J. Albrecht

U.S. Global Change Research Program (USGCRP) Review
Terms of Reference

- The President's Science Advisor will submit to the National Research Council (NRC) for its review on January 29, 1990, a report entitled, "Our Changing Planet: The FY 1991 U.S. Global Change Research Program," which outlines the FY 1991 USGCRP research plan.

- The purpose of this review is to examine if the research plan represents the highest priority research activities (i.e., the research, data collection, and modeling programs) needed to reduce the scientific uncertainties associated with related global change issues.

- NASA's Earth Observing System (EOS) is an integral part of the total USGCRP. As part of the overall review, there are several issues related specifically to EOS that the review should address:

  1. Does EOS collect the environmental parameters that are reflected in the USGCRP research priority framework and related policy issues described in "Our Changing Planet"?

  2. EOS is premised on the assumption that it is essential to collect global data on various environmental parameters simultaneously. How important is data simultaneity to the ultimate utility of the data? Can the requirement of simultaneity be applied more narrowly than proposed?

  3. Depending on the outcome on the question of simultaneity, are the EOS platforms, as currently configured, the optimal means for collecting this data, or are there better alternatives that are more cost effective or timely. These alternatives could include, for example, smaller multiple platforms flying in formation or additional near term precursor missions that are capable of flying subsets or preliminary versions of EOS instruments.

  4. Does the proposed EOS Data Information System represent the appropriate approach to support this long-term data collection and modeling effort?

- As it did with the FY 1990 USGCRP Plan, the NRC Committee on Global Change (CGC) will review the FY 1991 USGCRP Plan. In performing the review, the CGC should call upon any recent and current work in the NRC related to this request, for example, the current assessment of EOS now being conducted by the Committee on Earth Studies of the Space Studies Board. It is also recognized that the review may require additional experts with experience in developing and procuring complex remote sensing spacecraft, instruments, and data management systems.

- At the request of the NRC Executive Officer, the President's Science Advisor will provide support and any additional information pertinent to the review either directly or via the Committee on Earth Sciences and its member agencies.

- The NRC will provide a progress report on the review by April 1, 1990, with a final report due no later than July 1, 1990.

Appendix B

Comments on projects in the Science Priority Elements of the FY 1991 USGCRP

As part of its assessment, members of the Panel to Review the FY 1991 USGCRP reviewed brief descriptions of each of the projects identified in the Appendix of the FY 1991 version of *Our Changing Planet* published in January 1990. The reviews considered several aspects of the projects, including relevance to the goals of the USGCRP, readiness of the scientific community, and international linkages. The materials provided by the CEES for this review were of uneven quality and scope. The panel's reviews were consequently limited and should not be construed as either comprehensive or definitive. Brief summaries of the reviews, organized by science priority elements, are given below.

Climate and Hydrologic Systems

The FY 1991 plan for the USGCRP establishes important new activities that address critical aspects of climate and hydrologic systems. As yet, however, no area within this science priority is comprehensively or adequately defined. Not addressed, as yet, are effects of the hydrologic cycle on climate and on other elements of the earth system.

Significant new initiatives dealing with the management of global change data constitute a major budget element, particularly for NOAA and NASA. Some diversity is desirable in data handling, but the degree of coordination in the plans available suggests there may be excessive duplication and inadequate communication between agency laboratories carrying out similar functions.

Approaches to climate and hydrological systems in the USGCRP are largely process oriented or regional and applied only near the United States. The only identified observational initiatives with a global perspective are the oceanographic studies WOCE and JGOFS. No global approaches or climate initiatives are identified in the area of land-climate interaction. There are new initiatives in oceanography from several agencies but many are regional. A comprehensive approach to polar issues is also lacking. In this science element, international planning has been quite productive, and the WCRP has developed several programs which reflect broad scientific input. Nevertheless, there are few apparent connections with the international programs of the WCRP or IGBP. U.S. involvement—GEWEX and accelerated funding for WOCE would help remedy this deficiency.

Two agencies, DOE and NASA, are making efforts to address the issue of the role of clouds in the earth's radiation and heat budget. Within NASA the role of clouds is addressed under several initiatives. These include the production of global data sets in the Earth Radiation Budget Experiment, which are crucial for this question, the continuation of the ISCCP program of cloud global data sets, and the First ISSCP Regional Experiment program of cloud-radiation process studies, which has been demonstrably successful but is in need of further support. The DOE effort in this area is focused on developing a network of surface observations. It was not clear to us how this effort is to develop the necessary parameterizations for cloud radiation in climate models, which are needed to improve confidence in model projections of future climate change. We concluded that there are still major gaps in the approach to clouds in the USGCRP, even though this is the top priority in the program as presently defined.

NOAA plans exemplify mechanisms for coordinating agency efforts with other agencies and with the academic community. The TOGA program is a very successful example of coordination with the academic community and joint funding with the National Science Foundation. NOAA has been innovative in enlisting a broader community in formulating the plans for this important agency project. There are promising plans to expand this coordination in GEWEX, WOCE, and JGOFS. Some programs included in the Climate and Hydrologic Systems science element by other agencies show a lack of balance and focus that might well be remedied by involving a wider community in their formulation.

Biogeochemical Dynamics

The emerging field of biogeochemical dynamics is among the better developed in the global change effort, and many projects have now been developed over the past five or ten years. Most of them are directly relevant to meeting the high priority needs of the USGCRP; they are included in the FY 1991 budget and deserve strong support. Two areas require additional emphasis. One is atmospheric chemistry modeling directed at the troposphere on regional and continental scales. Such models complement climate models and must be developed in parallel with them. The second is marine chemistry, of both surface and deep water, to augment efforts that currently address only CO_2.

For many projects in this science element, space-based observations are crucial for proper calibration, coverage, and data assimilation. A strong Earth Probes program would help to meet these needs, as would EOS, given its more comprehensive set of sensors and longer duration.

In many areas in biogeochemical dynamics, as in other fields of global change research, there are serious limitations in human resources. The full spectrum of proposed grant, workshop, and post-doctoral support is needed to build the necessary cadre of workers. More important is the assurance of a sustained commitment to global change research to make careers in this area attractive.

International collaboration is crucial for most research projects dealing with biogeochemical dynamics. The USGCRP should encourage these linkages, through IGAC and JGOFS, and with particular attention to Africa and Asia where participation of countries from these continents are currently lacking. Such links could be immediately fruitful through the joint development of emission inventories.

Ecological Systems and Dynamics

The highest priority element in this area (Long-Term Measurements of Structure and Function) is poorly addressed by current and proposed programs. The NSF LTER program, included in the FY 1991 USGCRP budget, was established with long-term monitoring in mind, but it will be difficult to use data from a small number of sites to synthesize information on regional or global changes. The goal of the current LTER program to provide long-term monitoring is subverted by emphasis on process-level experiments and intersite comparisons. Nor do the established LTER sites sample areas of greatest change. The adaptation of the LTER network to needs of the USGCRP is a critical problem which should be addressed by a thorough, external review.

In Priority 2 (Response to Climate and Other Stresses), USDA has a very good program in response to changes in ultraviolet light, and a good track record in understanding response to changes in temperature. More work on plant respiration is needed. Priority 3 (Interactions of Physical and Biological Processes) has been funded through the Ecosystems Studies Program at NSF. Although the track record is excellent, the program is now harmfully short of funds to support a healthy research community. Within

Priority 4 (Models of Interactions, Feedbacks and Responses) and Priority 5 (Productivity/Resource Models), the future plans in NSF Ecosystem studies and DOE CO_2 research programs seem promising.

The most promising programs are those offered by NOAA, EPA, and DOE. DOI elements are only vaguely defined, with the exception of streamwater quality. Within the USDA, programs to assess system response are well-founded, while those offered by the Soil Conservation Service reflect conventional interests, such as soil classification, with little apparent effort to modify anything to the particular needs of the USGCRP, such as the interaction of soils with vegetation.

As in other areas, a critical shortfall of scientists and technicians needed for research can be foreseen, and it must be prevented if the USGCRP is to be sustained into the next century.

Earth System History

The projects included here involve mainly data archiving initiatives and paleoenvironmental studies (chiefly paleoclimatic and paleoecological). The data archiving efforts are important—for example, the plans within NOAA to double the funding for its efforts in this area—because determining data quality and temporal resolution are critical in reconstructing the past. Examples are the reconstructions developed through CLIMAP, COHMAP, and SPECMAP. However, a realistic assessment and better definition of where efforts should be concentrated require more information than was available to us on how the activities related to earth system history are funded outside of the USGCRP. For example, NSF funds a great deal of Quaternary paleoclimatic study within programs that are not included in the FY 1991 budget for the USGCRP.

A question repeatedly raised regarding this science priority is "What is included and what is not?" The IGBP effort in Past Global Changes (PAGES program) has identified two domains of temporal emphasis: the last 2000 yrs; and the late Quaternary period that embraces the major glaciations and the abrupt changes of climate (occurring over periods of 10 to 1000 yrs) that have punctuated past glaciations and interrupted glacial/post-glacial transitions, such as the Younger-Dryas event. The forth-coming report of the CGC addresses similar needs for the USGCRP science element on earth system history, with added attention to the changes of the more distant past that may yield information on fundamental processes in the earth system that could apply to anticipated, contemporary change. The addition seems to us a healthy one. It is still true, however, that in reviewing the projects included in this science element, as with those in the Solid Earth Process priority element, the more recent history of the earth system (i.e., chiefly the Quaternary) is probably the more important for understanding the global changes that are anticipated in the next 100 years.

We also note that the United States is being asked to play a special role in this area of the international program by co-sponsoring, with Switzerland, the Core Project Office for the PAGES program in Bern. We see this as an opportunity to strengthen U.S. science in the area at a minimal investment.

Human Interactions

The human interactions component of the USGCRP introduces many complexities, mainly because it demands linkages between the natural and social sciences that have not existed in the past, and because within the social sciences, experience and development in this field of endeavor are not as far along as in other areas of global change research. The projects in the FY 1991 budget within this science element appropriately include a number of efforts to establish the base-line data required for understanding human interactions (e.g., land cover change, emission flux), create accessible data pools and electronic archives, and develop global emission modeling. Still, improvements are needed in several areas. Many of the projects do not focus on the underlying and most central concern, which is the human forces that drive global change (e.g., land use change, industrial metabolism, population growth). As a result, what is proposed appears peripheral to what might be termed the urgent goals of the program.

The danger is that simplistic and aggregate data and assumptions on the human driving forces of global change, on impacts, and on natural resources will be used uncritically in other elements of the program. Emphasis must be placed on global data sets and on studies that link industrial metabolism and land-use change on regional and global scales in order to develop a more sophisticated understanding of the societal actions that cause global change.

The program defined by projects in the FY 1991 budget in this area differs fundamentally from that recommended by the CGC (NRC 1988). The recommendations of the latter were for research on the human causes of global change; the FY 1991 budget for the USGCRP invests chiefly in the impacts of global change. The program must address both aspects.

The program on human dimensions within NSF is to be commended for encouraging social scientists to consider global human systems as well as regional complexities. However, several potential problems should be watched for as this program develops: (1) much of the "global" research needed in the first stage is that of synthesis, which runs counter to the traditional NSF emphasis on original research and consequently may not fare well in the traditional peer review process; (2) encouraging social scientists to participate in the effort will bring in many individuals who will require education on global change and nature-society interactions. This need should be addressed and provided for from the start; and (3) mechanisms are needed to ensure that on-going relevant work is not excluded.

In addition, we recommend that particular efforts be undertaken to strengthen international linkages in the study of human interactions. There is as yet no established counterpart in the international social sciences community to the IGBP or the WCRP, although better understanding about human interactions is widely acknowledged as necessary in meeting the goals of the programs.

We singled out the Human Dimensions priority as the most critically underfunded in the FY 1991 budget for the USGCRP, a fact that may reflect the state of readiness of the field. At the same time it is unrealistic to expect the social science community to bend its efforts toward the ends of the program unless there are funds adequate to sustain participation and projects identified to channel it. If the FY 1991 budget recommendations are indicative of what will follow, there is neither enough funding nor adequate project definition for the human interactions component to keep abreast of the demands of the program.

Solid Earth Processes

The USGCRP has evolved to the point that the two earth science program areas (solid earth processes and earth system history) can be reevaluated in light of developments since they were first incorporated in the program. The element on Solid Earth Processes receives the fourth largest funding of all the science elements, primarily because NASA activities in the area account for three-fourths of its funds. We did not have details on the NASA projects comparable to the information from other agencies, and it was not possible to assess the relevance of the projects. A feature of projects within this science element is that several were developed prior to the USGCRP, and were probably not selected on the basis of what was most needed for the specific focus of the program. Examples are the RIDGE and GEODYNAMICS activities included in the NSF budget for FY 1991. We recommend that these projects be reevaluated with respect to their qualifications as "focused" projects in the program, and that steps be taken to establish more uniform standards among agencies as to what constitutes "focused" and "contributing" projects.

As in several other science priority areas, what appears to be lacking is a "zero-based" assessment of what the program as a whole requires, as opposed to an assemblage of what was already there through inheritance. The lack of initial direction can probably be expected at this stage in the early implementation of the program. We can hope for a more coordinated effort in the program with further development of the Science Priority Task Group of the CEES. A notable need that is not addressed in this area is the study of soils, a key component in global change, including the response of soils to global change and the relationship of soils to the earth system.

Solar Influences

Initiatives in this area are wholly within NASA and NSF; they represent a reasonable attack on the policy-relevant questions that are included in the FY 1991 budget description. Whether these are the most appropriate questions for the specific focus of the USGCRP, or, in the case of the NSF budget, whether they merely justify previously initiated programs such as CEDAR and the proposed GEM, calls for review. We recommend that these be reassessed by the Task Group as to determine if they might be better classified as "contributing" rather than "focused" projects in the USGCRP, particularly in light of their emphasis on conditions in "geospace" and their potential importance as a significant climate driver. The proposed RISE initiative, directed at specifying variations in the radiative inputs from the sun, will address more fundamental issues in the area.

NASA initiatives, including UARS and EOS, more clearly belong in the "focused" category.

We suggest that CEES seek mechanisms whereby the scientific community can provide advice on the scientific priorities and research needs for this science element. For example, the priority is one of two that were initiated by the CEES without the benefit of definition from the CGC. The CGC plans to establish an additional Working Group on the subject, which should be called upon to aid in future program definition.

Earth System Modeling

Efforts to upgrade global climate models or build toward complete global system models are not yet seriously under way in the United States. The NOAA initiative in the FY 1991 budget, which proposes a TOGA center to address seasonal-interannual forecasting and makes significant efforts toward "extended range" forecasting, will contribute to meeting this need. NOAA also plans to focus efforts on developing modeling capabilities for global change on the time scale of decades to centuries. Other agencies may wish to join in the latter effort. In order for this activity to be a major integrating force in the USGCRP, it is also necessary to ensure that university community involvement is sufficiently large. The CHAMPP initiative within DOE addresses an important technological issue, which is the need for much more powerful computational resources and programming algorithms to make use of these capabilities.

At present, the most advanced modeling centers in this country principally address the atmosphere, although there are some capabilities for global ocean modeling. Development of the necessary land component is only beginning, as is coupling with global tropospheric and stratospheric chemistry. A number of approaches to modeling ocean biogeochemical cycles are also under development. There are as yet no significant efforts to couple terrestrial biogeochemical cycles and ecosystem dynamics in earth system models. Whether such highly interdisciplinary efforts can build upon existing major programs—i.e., as adjuncts to climate models—or whether they should be developed ab initio requires further examination.

The CGC is currently developing in its forthcoming report specific recommendations regarding an overall U.S. strategy for the development of integrated earth system models. Some of the important issues that need to be considered are centralization vs. distributed models, the appropriate roles of university scientists of centers vs. those of federal agencies, the nature of needed connections with impact studies, and the role of the social science community in the overall modeling effort. As noted earlier in this report, a significant need in the USGCRP as defined in the FY 1991 budget is definition of the appropriate mechanism for evaluating model results and impact studies and delivering them to policymakers.

Data and Information Systems

This component of the USGCRP has contributions from three agencies: NOAA, DOE, and NASA, in which the initiatives of NASA dominate. NASA elements include both observational and data systems, including Earth Probes, UARS, TOPEX, and NSCAT, which are all essential near-term components of the USGCRP. EOS has three parts: the near-term support of development of the EOS data and information system (EOSDIS), support of interdisciplinary studies, and development of spacecraft hardware for EOS, to be launched toward the end of the decade. An evaluation of EOSDIS is included in Chapter 8 and Appendix C of this report.

Within NOAA, the major activities proposed are data management, climate diagnostics and data base development on upper ocean/marine surface observations, sea level observations, and development and testing of measurement technique. As in other areas, it is important that these efforts involve the user community as much as possible.

Documenting Global Change

This area is included in the CEES program for the USGCRP as an integral part of the effect on Data and Information Systems. A prioritized list of the global variables that require sustained, long-term measurement has yet to be defined with broad consensus in the USGCRP. The NASA Earth System Sciences Committee presented such a list in its final report in 1988, which could serve as a starting point for broader and more current review, if not the final product. The EOS program has since defined, de facto, a proposed eventual space-based component to be complemented by measurements in the Earth Probe series, albeit over shorter periods of time.

We believe that the detection of significant long-term global change is so central to the goals of the USGCRP, and so clear an obligation to future scientists, that it should be considered explicitly for added emphasis in the early stages of the program. The emphasis would ensure that the issue is addressed directly and in time to make a difference in planning observation systems, both in space and from the ground and the oceans.

Appendix C

Prototyping for EOSDIS

This Appendix was prepared by the Panel to Review NASA's Earth Observing System in the Context of the USGCRP.

Unique Challenges of Global Change Data Management

The types of data management now being undertaken are truly without precedent. Any process in the atmosphere or ocean is intricately entwined with numerous other processes because researchers are looking at the subsystems of an "object," the Earth. Gaining understanding and an ability to predict synoptic changes in the global system will require detecting and studying numerous interconnections among processes.

Many different models are available for organizing a database, such as hierarchical, relational, and networked. Prototyping will be needed to learn how scientists will work with EOSDIS so that organizational schemes optimally suited to the functioning of different components of the system can be selected.

Use of Data Archives as a Research Library

Data collected under EOS and related Earth observing programs will form the research library for scientists trying to answer crucial questions about global change. There is no argument about the imperative to improve understanding as rapidly as possible.

How are libraries used for research? The experience base is partly with libraries of printed material. Another relevant source is the on-line literature search. In the library, one starts with a card catalog, which has limited but valuable cross references. The on-line search allows logical combinations of subjects or keywords, which improves the precision of the search. But serious study invariably brings the researcher down to the level of the book index, and to a lot of old-fashioned browsing. If the books are in stacks with limited or no access, the job becomes increasingly difficult. On-line literature searches provide a somewhat more powerful ability to locate information that conforms to user-specified requirements. Its limitations result partly from the fact that only key words can be searched.

Metadata, defined in the broad sense as the collection of important information about data, will form the library catalog for global change research. Research will require finding metadata and data through interrelationships. If this cannot be done, scientists will find themselves thwarted in trying to trace complex causal effects, the understanding of which are the objectives of global change research. As with libraries, the more completely the metadata are accessible to the scientist, the more effective will be the research. Effective accessibility must include more than the equivalent of the card catalog. The slowness of finding a comprehensive set of relevant research material in a library, via indexes, tables of contents, and text scanning, will not be acceptable for answering urgent questions about global change. Furthermore, an efficient system will assist in keeping up with the high rates at which EOS data will be accumulated.

Database Requirements for Scientific Metadata

The performance of existing systems for managing complex compilations of scientific data is not encouraging. For example, while catalogs of "available" planetary data are published, many potential users tell stories of their failure to obtain the data despite determined efforts. The successes, where they exist, can be instructive for EOSDIS. For example, one very effective geoscience data management system is available at the National Center for Atmospheric Research. Its success has been due in large part to the development of data management systems, quality controls, and data archives at a scientific center in consultation and collaboration with scientists.

One of the few true prototypes is the system built at the NASA Space Science Center for plate tectonic measurements, which are unusually independent of other geophysical events. Even for that dataset, for which queries might appear to be relatively predictable in nature, a highly sophisticated, intelligent system of layers (plus a natural language interface to the user) is used to process queries. The levels of complexity introduced in global change research by following interactions among processes are absent from the tectonics dataset, however.

The observation that emerges is that little is known about how scientists would use an EOS data management system, and it is premature to define it. Much is known about how to manage bank records and airline reservations and inventories. They involve large numbers of relatively simple and highly predictable transactions, e.g., queries and data operations. Such systems must keep instantaneous track of all changes, such as bank balances, and airline seating availability. The requirements for global change are different. Except for new entries, there will be little change in metadata already entered, so that keeping track of the system state on a second-by-second basis will not be needed. But the queries posed will tend to be complex and of a highly unpredictable nature. They will be driven by the mandate to the scientist: to understand connections between different elements of the system, to understand underlying causes, and to develop the an ability to predict. Research is needed to learn how scientists will work with EOSDIS through prototyping to select a system well suited to the functions of global change research.

Timely Access to Large Datasets

The history of dealing with large datasets is also discouraging. Responses to data requests can be slow, and the NASA and NOAA datasets are known to be difficult to obtain. Current datasets in both agencies are minuscule compared with those in the predicted EOS archives. Obtaining timely answers to pressing issues of global change that may affect society will require performance at a hitherto undreamed of level. Prototyping of this aspect of data management can be done with the datasets already in existence, and much could be learned by developing a system to efficiently locate and deliver data from existing archives.

Missing and Bad Data

There is a continuum of problems with data that needs to be addressed in any data management system and that can be explored with prototype experiments. Potential problems with data range from the predictable corrections that must be made on any dataset, through data tagged as "bad" according to some set of criteria, to data that is missing because either an expected measurement was not made or "bad" data were eliminated from the dataset.

First, it is necessary to provide complete information about locations of missing data, so that the user does not discover until after investing both human and computer time that a dataset chosen for analysis is unusable.

Second, decisions must be made about how to handle a segment of data that is "bad" from one point of view but may contain useful information for some other research purpose. Experiments must be done by scientists using data for research purposes and for checking the effectiveness of different approaches to their problems. Experimentation must then be done on how to integrate the method into an overall data management scenario.

Another concern is one of data integrity. Scientists should begin using data as quickly as possible after obtaining it because standard error checking algorithms may not identify data that look useable but do not make sense physically, perhaps, for example, because of a malfunctioning instrument. Solutions may involve getting data on-line rapidly (which alone does not guarantee that it will be used quickly) and developing sample analysis programs with more sophisticated algorithms that will reveal subtle but systematic nonsense errors.

Visual Browsing

Clearly, browsing is already an important element of data management. Less clear is how, in the future, it will be possible to use this technique for any selection of data as a skimming technique. The process of locating data to browse will thus use the tools mentioned earlier in the discussions of data archives and metadata for research. Prototyping of browsing must include both workstation visualization tools and the full range of data management tools that make it possible to find data likely to be of interest.

Access by Many

Prototypes should reflect the situation that will obtain in the EOSDIS era; that is, they should provide easy access to everyone with a need, just like the analogous library. While those involved can be expected to determine the design of the prototypes, any who need access to the prototypical systems should be allowed it, within reasonable financial constraints. Only in this manner can the prototypes be tested for their effectiveness in serving the needs of the broader scientific community. Lessons learned from such tests will be the real products of prototype development that must be incorporated into the design of EOSDIS.

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ACRONYMS

ACRIM	Active Cavity Radiometer Irradiance Monitor (NASA)
ADEOS	Advanced Earth Observing Satellite (JAPAN)
AIRS	Atmospheric Infrared Sounder (NASA)
ALT	Altimeter (NASA)
AMSU	Advanced Microwave Sounding Unit (NOAA and UNITED KINGDOM)
AVHRR	Advanced Very High-Resolution Radiometer (NOAA)
BEST	Bilan Energetique de la Système Tropicale (FRANCE)
CEES	Committee on Earth and Environmental Sciences
CGC	Committee on Global Change (NRC)
CERES	Clouds and Earth's Radiant Energy System (NASA)
DAACs	Distributed Active Archive Centers (NASA)
DMSP	Defense Meteorological Satellite Program (DOD)
DOD	Department of Defense
DOE	Department of Energy
ELV	Expendable Launch Vehicle
EOS	Earth Observing System (NASA)
EOSDIS	EOS Data and Information System (NASA)
EOSP	Earth Observing Scanning Polarimeter (NASA)
EPA	Environmental Protection Agency
EPOP	European Polar Orbiting Platform (ESA)
ERBE	Earth Radiation Budget Experiment (NASA and NOAA)
ERS	Earth Remote-Sensing Satellite (ESA or JAPAN)
ESA	European Space Agency

GEWEX	Global Energy and Water Cycle Experiment (WCRP)
GGI	Global Positioning System Geoscience Instrument (NASA)
GLRS	Geosciences Laser Ranging System (NASA)
GOES	Geostationary Operational Environmental Satellite (NOAA)
GRM	Geopotential Research Mission (NASA)
GTE	Global Tropospheric Experiment (WCRP)
HIMSS	High-Resolution Microwave Spectrometer Sounder (NASA)
HIRDLS	High-Resolution Dynamics Limb Sounder (NASA)
HIRIS	High Resolution Imaging Spectrometer (NASA)
HIRS	High-Resolution Infrared Radiation Sounder (NOAA)
ICSU	International Council of Scientific Unions
IGAC	International Global Atmospheric Chemistry Program (IGBP)
IGBP	International Geosphere-Biosphere Program (ICSU)
ISCCP	International Satellite Cloud Climatology Program (WCRP)
ISLSCP	International Satellite Land Surface Climatology Program (WCRP)
ITIR	Intermediate Thermal Infrared Radiometer (JAPAN)
IWG	Investigator Working Group (EOS)
JGOFS	Joint Global Ocean Flux Study
LAGEOS	Laser Geodynamics Satellite (NASA)
LAWS	Laser Atmospheric Wind Sounder (NASA)
MISR	Multi-angle Imaging Spectro-Radiometer (NASA)
MLS	Microwave Limb Sounder (NASA)
MODIS	Moderate Resolution Imaging Spectrometer (NASA)
MODIS-N	MODIS Nadir-Viewing (NASA)
MODIS-T	MODIS Tilt-Viewing (NASA)
MOPITT	Measurement of Pollution in the Troposphere (NASA)
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
PAP	Payload Advisory Panel (EOS)
SAFIRE	Spectroscopy of the Atmosphere using Far Infrared Emission (NASA)
SAGE	Stratospheric Aerosol and Gas Experiment (NASA)
SAR	Synthetic Aperture Radar (NASA)
SBUV	Solar Backscatter Ultraviolet (NOAA)
SCANSCAT	Advanced Dual Pencil-Beam Scatterometer (NASA)
SCARAB	Scanner for Radiative Budget (France/USSR)
Sea WiFS	Sea-Viewing Wide-Field Sensor (NASA)

SIR	Shuttle Imaging Radar (NASA)
SOLSTICE	Solar Stellar Irradiance Comparison Experiment (NASA)
SPINSAT	Special Purpose Inexpensive Satellite (DOD)
SPOT	Systeme Probatoire pour Observation de la Terre (FRANCE)
SSB/CES	Space Studies Board's Committee on Earth Studies (NRC)
STIKSCAT	Fan-Beam Scatterometer (NASA)
SWIRLS	Stratospheric Wind Infrared Limb Sounder (NASA)
TDRSS	Tracking and Data Relay Satellite System (NASA)
TES	Tropospheric Emission Spectrometer (NASA)
TIROS	Television and Infrared Operational Satellite
TOGA	Tropical Ocean-Global Atmosphere Program (WRCP)
TOMS	Total Ozone Mapping Spectrometer (NASA)
TOPEX	Ocean Topography Experiment (NASA)
TOVS	TIROS Operational Vertical Sounder (NOAA)
TRACER	Tropospheric Radiometer for Atmospheric Chemistry and Environmental Research (NASA)
TRMM	Tropical Rainfall Measurement Mission (NASA)
UARS	Upper Atmosphere Research Statellite (NASA)
USGCRP	U.S. Global Change Research Program
USGS	U.S. Geological Survey
WCRP	World Climate Research Program (WMO)
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment (WCRP)