Toward an International Geosphere-Biosphere Program

A Study of Global Change

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Report of a
National Research Council Workshop
Woods Hole, Massachusetts
July 25–29, 1983

Commission on Physical Sciences,
Mathematics, and Resources
National Research Council

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INTERNATIONAL GEOSPHERE-BIOSPHERE PROGRAM WORKSHOP
Woods Hole, Massachusetts
July 25-29, 1983

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PREFACE

The real connections that link the geosphere and biosphere to each other are subtle, complex, and often synergistic; their study transcends the bounds of specialized, scientific disciplines and the scope of limited, national scientific endeavors. For these reasons progress in fundamental areas of ocean-atmosphere interactions, biogeochemical cycles, and solar-terrestrial relationships has come far more slowly than in specialized fields, in spite of the obvious practical importance of such studies. If, however, we could launch a cooperative interdisciplinary program in the earth sciences, on an international scale, we might hope to take a major step toward revealing the physical, chemical, and biological workings of the Sun-Earth system and the mysteries of the origins and survival of life in the biosphere. The concept of an International Geosphere-Biosphere Program (IGBP), as outlined in this report, calls for this sort of bold, "holistic" venture in organized research--the study of whole systems of interdisciplinary science in an effort to understand global changes in the terrestrial environment and its living systems.

The National Research Council IGBP Workshop at Woods Hole in July 1983 considered the major problems for research in five areas that might naturally be coordinated in such a program: the atmosphere, oceans, lithosphere, biosphere, and solar-terrestrial system. A unifying and pervasive theme of the Workshop was global change, on all time scales, from the slow recurrence of the Ice Ages to the shortest transient phenomena. Of pressing importance is the need to understand the often deleterious effects of modern man on natural processes, such as the inevitable climatic impact of carbon dioxide loading of the atmosphere since the industrial revolution. Progress in

understanding global change will require extensive and well-organized observations made over much of the Earth and over a long period of time. The scope of such an effort requires international cooperation and interdisciplinary emphasis.

If we believed--as once in fact we did--that ocean circulation was slow and unchanging, we could hope to establish its fundamental patterns from the collection of random oceanographic observations from all times past. We could mix data taken by Captain Cook on the *Endeavour* with soundings from the most recent cruise of the *Columbus Iselin*. But the ocean is constantly changing, and the element of time is all important. Synoptic observations or time-oriented measurements in conjunction with time-dependent models are today indispensable. In place of a *Challenger* on a lone voyage of exploration we now need a fleet of research vessels taking coordinated observations, accompanied by downlooking spacecraft that can survey entire ocean basins with high spatial resolution on a synoptic basis. All of these must be supported by sophisticated modeling efforts.

If we believed that the Earth was a constant system in which the atmosphere, biosphere, oceans, and lithosphere were unconnected parts, then the traditional scientific fields that study these areas could all proceed at their own pace treating each other's findings as fixed boundary conditions. However, not only is the Earth changing even as we seek to understand it--in ways that involve the interplay of land and sea, of oceans, air, and biosphere--but we cannot even presume that global change will be uniform in space and steady in time. World climate and the acknowledged complexity of climatic change are cases in point. Needed to resolve this complex of change and interplay are coordinated efforts between adjacent scientific disciplines and programs of synoptic observations focused on common, interrelated problems that affect the Earth as a whole. Through this kind of international and interdisciplinary collaboration, we can hope to identify the mechanisms and causes of global change. At the same time we can illuminate areas of particular need and emphasis in each of the related disciplines.

A major challenge to an IGBP will be that of understanding the causes and effects of climate change. Variations in the Earth's climate appear to follow from a long and convolved set of interactions including human and other biological activity, solar radiation, volcanism,

ocean circulation, polar ice and land effects, and the chemistry and dynamics of the atmosphere itself. Also involved on long time scales are the varying gravitational perturbations of the planets and the Moon on the orbit of the Earth and perhaps the varying density of interstellar matter encountered by the Sun in recurrent passages through the spiral arms of the Galaxy. No single factor is clearly dominant. In most cases we must presume, moreover, that any detectable change is the result ultimately of the interplay, feedback, and possible amplification of many causative factors.

The recovery and interpretation of a wide variety of historical, paleontological, and geochemical records provide most of what is known of the history of climate and what insights we have as to the responsivity of the terrestrial environment to internal and external forcing. Tree-ring data, lake deposits and pollen samples, and ocean and polar ice cores are natural diaries that contain information on past meteorological conditions, sea temperatures and ice cover, atmospheric composition, biotic conditions, crustal magnetism, and solar behavior. Such records know no national boundaries, nor is their interpretation the exclusive province of a specific scientific discipline. The critical reading of these data and the ability to relate what is told of global change and interaction are necessary steps toward reliable prediction of future trends in climate and biological response.

Tropospheric chemistry--a field of study that hardly existed a dozen years ago--now looms as ever more important in fixing the conditions for life on Earth. Local atmospheric pollution and the generation of global haze are obvious factors in the habitability of the planet. In addition, the troposphere is both the ultimate source and the ultimate sink for the trace chemistry of the stratosphere, which in turn modulates the amount and spectral distribution of sunlight received at the surface of the Earth. To understand the stratosphere we must know the chemical as well as the dynamical behavior of the global troposphere. Stratospheric ozone is subject to tropospheric chemistry and sensitive to anthropogenic modification. The best-known and most throughly studied green house gas is carbon dioxide, whose role as a perturber of future surface temperature is a subject of keen international concern. But it is now clear that gaseous leaks from old refrigerators and even the bacteria in the gut of cattle are insidious rivals to carbon dioxide as contributors to global temperature

change. Chlorofluoromethanes, nitrous oxide, and methane appear to contribute 70 percent as much to green house warming as does carbon dioxide. Methane in the atmosphere is increasing at more than 1.5 percent (60 x 10^6 metric tons) per year, and we are completely at a loss to explain how it is conserved.

The power of new technologies for remote sensing of atmospheric, geological, biological, and oceanographic conditions promises to revolutionize our grasp of global conditions and our understanding of global change. In the past, for example, our knowledge of the sea floor was gained from shipbaord by reflecting sonic waves off the ocean bottom. Along the heavily trafficked sealanes in the North Atlantic, the soundings obtained by many ships combined to provide a reasonably well-filled map. Far less was known of larger areas of the oceans of the world where commerce was less frequent. SEASAT, following its deployment in 1978, demonstrated the power of global seafloor mapping from the vantage of Earth orbit. Its radar altimeter portrayed the large features of sea mounts and ocean trenches in an immediately obvious way. Surprisingly, however, when noise corrections were made to the same data, an unexpected range of seafloor features of much finer detail was clearly revealed. New features, never before mapped, include underwater volcanoes, tectonic fracture zones of crustal plates, swales of ocean crust with unusual gravitational characteristics, and a smooth underwater plateau as large as the state of California. Fracture zones mapped from the perspective of space can be followed across entire ocean basins, even where they are covered by sediment.

Advantages equally great have come in the past 20 years from orbital sensing of the Earth's biota. Much of the motivation has been to develop means of assessing conditions for the world production of food, fiber, and fuel from renewable biological resources. The focus has been on agricultural crops, forests, and rangeland of economic importance, and the principal tool has been infrared mapping. In recent years, microwave techniques have come to the fore, offering added capability in sensing through overcast and penetrating more deeply into canopies of vegetation.

It is hard to exaggerate the impact of orbital platforms and new technology in the field of solar-terrestrial physics. The ability to make in situ measurements in the vast domain between the middle atmosphere and interplanetary space has revealed the complex topography of near-

Earth space and a tangled web of connections that link the lower atmosphere to the Sun. Among the early findings from spacecraft was the unexpected scale and structure of the extended magnetic field of the Earth and the existence of an ordered but inconstant solar wind of charged particles that fills the Sun-Earth space. Orbital measurements of the meteorologically important fluxes of solar radiation are at last providing quantitative data on the perennial question of the influence of solar variations on weather and climate. The cavity radiometer on the Solar Maximum Mission spacecraft, launched in 1980, has made continuous measurements of the total radiative flux from the Sun with a temporal resolution of less than a minute and a short-term accuracy of about 10^{-5}--about 4 orders of magnitude better than what could be done from the ground. Quickly found were depletions of about 0.1 percent lasting for weeks, that result from the masking of the solar disk by sunspots. Future measurements should establish whether a similar variation accompanies the 11-year sunspot cycle.

Ultraviolet imaging from space has literally shown us the Earth in a new light. The aurora now stands revealed in detail that escaped the previous 100 years of observation. Reel-down instruments suspended from balloons provide direct profiles of the chemical composition of the middle atmosphere from tropopause to stratopause; tethered instruments from future satellites promise similar capabilities for characteristics of the lower thermosphere.

These comments sample the content of the discussions that took place at the IGBP Workshop. From the report itself it will be clear that rich opportunities are in store for the earth sciences in the future and that the world scientific community should prepare to meet the challenges boldly.

Herbert Friedman, *Chairman*
International Geosphere-Biosphere
Program Workshop

CONTENTS

SUMMARY

The Workshop reviewed the major problems for research in the atmosphere, oceans, lithosphere, biosphere, and solar-terrestrial relationships. A unifying theme is global change. Beyond the intellectual drive to understand basic scientific interrelationships is the practical need to gain a better grasp on how to manage the environment and global life-support systems.

A majority conclusion was reached that an International Geosphere-Biosphere Program (IGBP) under the auspices of the International Council of Scientific Unions (ICSU) could provide an effective vehicle for coordinating global measurements from space platforms and ground-based observational networks, exploiting new technologies for observations, implementing improved capabilities for data management, and placing proper emphasis on mathematical modeling with advanced computational facilities.

Unlike the comparatively short-lived International Geophysical Year (IGY), an IGBP must be designed as a long-range, interdisciplinary program. Effective planning over the coming several years could inaugurate a program that would begin to take shape toward the end of this decade and reach maturity in the 1990s.

The Workshop participants urged that such planning begin immediately within national organizations and in all the interested adhering bodies of ICSU. An important target date for a first assessment of plans brought forward from all sources would be the ICSU General Assembly in September 1984.

In implementing an IGBP, careful attention must be paid to all relevant nationl and international programs already conceived and in various stages of progress. Proper planning should guarantee that these programs are

carried forward effectively. The success and timeliness of an IGBP is in large part predicated on gains in understanding as well as a desire for greater interaction between neighboring disciplines starting to emerge from these programs.

1

INTRODUCTION

A generation ago researchers concerned with the basic sciences of the Earth joined together in a unifying effort, the International Geophysical Year (IGY). The IGY was an outstanding success, both scientifically and politically. During 1957-1958, coordinated geophysical observations were gathered from pole to pole, and these observations and the research and monitoring that followed have significantly improved our understanding of the physics of the Earth. Thousands of scientists, from 67 nations, shared knowledge, purpose, and tools and created a spirit of cooperation and good will that transcends political differences.

Studies of ecological and biological processes were essentially neglected during the IGY, as were many questions requiring multidisciplinary approaches for their solution. These questions have become increasingly prominent since the IGY. The contemporary concern for the environment has heightened awareness of the need for increased scientific understanding of biogeochemical cycles and of the links between geophysical and biospheric processes. The desire to explore possible future conditions for life on Earth and the role of human activities in shaping those conditions lend urgency to developing the basic scientific knowledge of the geosphere and biosphere. It seems clear that this knowledge will only come from a comprehensive understanding of the historical evolution of the Earth and the dynamics of global change.

Since the IGY, there have been several major international programs, such as the Global Atmospheric Research Program and the International Magnetospheric Study, that included coordinated observations on a global scale. These programs have contributed significantly to our knowledge of geophysics and, in the case of meteorology,

our ability to forecast weather. However, the observational programs have generally focused on narrowly defined problem areas rather than on the broad scope of linkages among components of the geosphere and biosphere. Often the programs have been too brief in duration to establish linkages between slowly varying cyclic processes.

Today we find a growing number of current and planned programs, international in scope, that have interdisciplinary breadth. These programs and their national and multinational components are vital to any more broadly based future geosphere-biosphere program. For example, the Scientific Committee on Problems of the Environment (SCOPE) of ICSU has catalyzed pioneering work over the last decade with its program on the biogeochemical cycles of carbon, nitrogen, sulfur, and phosphorus. The theme of biogeochemistry has now been endorsed by a group of U.S. scientists in plans for a NASA program on "Global Habitability." Examples of other current programs close in spirit to an IGBP are the the International Lithosphere Program (ILP), the World Climate Research Program (WCRP), and the Study of Travelling Interplanetary Phenomena (STIP). Each of these, of course, has many important components. For example, the WCRP embraces the planned World Ocean Circulation Experiment (WOCE), whose objective is to describe and understand quantitatively for the first time the large-scale circulations of the world's oceans and their influence on the atmosphere. This objective should be attainable in large part as a result of new remote sensing techniques. WOCE is dependent upon major satellite missions, such as the Topography of the Ocean Experiment (TOPEX) and the Geopotential Radar Mapper (GRM) of the United States and the Earth Resources Satellite (ERS-1) of Europe, as well as surface and subsurface observing platforms. These observational programs are well conceived now and should be carried forward with a sense of urgency.

To understand many geosphere-biosphere phenomena and their interactions, monitoring over long periods will be necessary. For example, to detect and separate anthropogenically caused climate changes from natural ones and to understand the mechanisms involved may require a decade or more of accurate global monitoring of atmospheric and sea temperatures, the amount and distribution of radiatively active gases, vulcanism and aerosols, solar and terrestrial radiation fluxes, and ice masses and sea level. Thus, it becomes important to continue

and strengthen existing global observing and monitoring programs (and their national components), such as the World Weather Watch (WWW), and perhaps re-evaluate others, like the International Global Ocean Services System (IGOSS) and the Global Environmental Monitoring System (GEMS), in view of the scientific goals of an IGBP.

These and other programs that may relate in conceptual or practical ways to an IGBP are summarized briefly in Appendix E.

2

THE POWER OF NEW TECHNOLOGIES

The IGY occurred at the dawn of the Space Age. The 25 years since the IGY have seen the development of remote-sensing techniques and space platforms, which have opened up major avenues to investigate important problems in the geosphere-biosphere. Significant strides have been made in describing solar-terrestrial relations and studying the atmosphere through the use of space technology. The new power of this technology in studying the lithosphere, oceans, and the biosphere has been demonstrated, for example, in mapping the oceanfloor and terrestrial ecosystems. New programs are planned to take advantage of these techniques in all the discipline areas; they should be supported preparatory to increased multidisciplinary activity in the 1990s.

Remote sensing is by no means limited to space platforms. Probing the solid Earth by seismic and electromagnetic waves or the oceans by acoustic tomography are important examples of the growing array of ground-based remote-sensing techniques that can unlock the mysteries of the planet Earth.

The potential of high-altitude balloons to explore directly the stratosphere has been enhanced by the demonstration of a "yo-yo" technique to lower and raise a payload repeatedly through a layer about 10 km thick beneath the balloon. A tethered satellite is proposed to facilitate repeated direct measurement of the ionosphere and mesosphere.

Improvements are being made in the quality and reliability of many in situ sensors, platforms for carrying them (e.g., buoys, long-duration balloons), and the use of inexpensive satellite links for data collection and platform location. The cost of some of these systems is

within reach of many countries that may wish to be involved in international cooperative research.

The development of communication and computer technologies also opens up new vistas of research not possible 25 years ago. The handling of complex models is one example. Perhaps of equal importance is the opportunity that these technologies present for collecting, processing, archiving, accessing, and exchanging data. Such information will be needed by the many discipline groups internationally whose intellectual efforts must be enlisted if answers are to be obtained to many of the challenging questions raised at the Workshop.

GOALS AND FINDINGS OF THE WORKSHOP

Invitees to the Workshop were asked to address several specific issues and problems:

1. Need and criteria for an IGBP. Are there significant benefits to be had from increased integration and coordination? Which activities for which reasons (geographical access, satellite coverage, and cost, for example) truly require international cooperation to be successful?

2. Identification of areas in which large measurement programs can serve multiple scientific needs. For example, monitoring of a variety of chemical and radiative processes in the upper atmosphere is essential to understanding both the modification of the ozone layer and the greenhouse effect. Can more efficient use of resources to fulfill global and temporal requirements be made through an IGBP-type program?

3. Identification of critical interdisciplinary problems, interfaces, and linkages. For example, climate variation is related to solar-terrestrial interactions, vulcanism, ocean circulation, and forest and ecosystem processes and is recorded by sedimentary processes.

4. Potential roles of U.S. agencies, for example, the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), and the Department of Defense in ocean, atmosphere, and solar-terrestrial programs; the U.S. Geological Survey, NSF, and NASA for land surface and lithosphere; the Department of Energy, the Department of Agriculture, NOAA, NASA, and others for biogeochemical cycles.

5. Relationships with existing international programs and projects, such as the Middle Atmosphere Program, the

World Climate Research Program, the World Ocean Circulation Experiment, the International Lithosphere Program, and others.

6. Review of relevant papers and plans in the area, including the Space Science Board study Toward a Science of the Biosphere, the NASA Global Habitability plans, the CSTR report on Solar-Terrestrial Research for the 1980's, documents of the World Climate Research Program, including plans for the World Ocean Circulation Experiment, the report of the National Research Council's (NRC's) Carbon Dioxide Assessment Committee, Changing Climate, the NRC's global tropospheric chemistry report, and reports of the Middle Atmosphere Program.

7. How should design of the IGBP be broadened, nationally and internationally, should the concept evoke enthusiastic support at the Workshop?

The participants (Appendix F) represented a broad cross section of the natural-sciences community in the United States. The breadth of the group led to a realization that the study of global change relevant to human welfare must encompass wider time scales and greater areas of investigation than had hitherto been proposed. In particular, it became evident that much information relevant to the future can be gleaned from study of the past. These considerations suggest that investigation of global changes in the geosphere and biosphere should encompass pertinent studies of solar-terrestrial relations, lithospheric processes and their interaction with the atmosphere and oceans, and the history of life as evidenced in the fossil record, as well as the more obvious core of dynamic and radiative interactions among the atmosphere, ocean, and biosphere.

At the same time, questions were raised about the underlying conceptual unity and coherence, as well as practical necessity, of an IGBP. While the overall finding of the NRC group was strongly supportive, the concept remains only broadly defined. The major conclusion of the Workshop was the importance of the topic of global change, and the major recommendation was for further development of programmatic concepts on the national and international levels. The issues and problems listed above must be addressed in more detail by various potential participating individuals and groups to arrive at a consensus both nationally and internationally.

An IGBP must cover the time span of major natural cycles, such as the 11- and 22-year solar magnetic cycles. The characteristic duration of some important processes in the biosphere is even longer. It would be most valuable to design an international program with such intrinsic stability that monitoring parameters of global change could be carried on with necessary fidelity for decades. ICSU could provide the continuity of administrative structure to coordinate an IGBP over the long range.

A report of this Workshop was presented as part of a colloquium on global change organized by ICSU on August 3, 1983, coincident to a meeting of its General Committee in Warsaw. The report was favorably received, and the General Committee recommended global change as a theme for one of the scientific symposia being arranged on the occasion of the ICSU General Assembly in Ottawa, Canada, September 1984. This decision constitutes an invitation to all constituencies of ICSU to develop detailed inputs to a comprehensive discussion meeting at Ottawa. If that discussion leads to ICSU endorsement of a program, several years of intensive planning will need to follow in order to initiate a well-coordinated scientific effort.

In implementing an IGBP, careful attention must be paid to all relevant international programs already conceived and in various stages of progress. Proper planning should guarantee that these programs are carried forward effectively and in due course meshed with moves to accomplish the major goals of an IGBP. With adequate support and proper planning the IGBP could reach full maturity in the 1990s.

Several other desirable characteristics for an IGBP should be mentioned. One is that it should enlist young scientists and help them plan careers around the many exciting problems described here. Another is that universities should be involved. Universities are where much of the most advanced research is performed, and their involvement has implications for the scale of problems to be studied and rates at which results might be obtained. Third, the program should be worldwide, involving both developed and developing countries. Finally, there should be easy, wide access to data and individual freedom of choice for researchers on problems in which to involve themselves.

4

THE SCIENTIFIC CHALLENGE

Unraveling the mysteries of the past evolution of the Sun and Earth and predicting the future evolution of this planet and its life forms depend on continued strength to tackle the intellectually challenging problems within each of the disciplines studying the geosphere and biosphere. However, Workshop participants emphasized those scientific problems and opportunities that are multidisciplinary and global in scope, often requiring international cooperation. The scientific challenges were considered from the vantage point of four broad research domains: solar-terrestrial, oceans and atmosphere, the lithosphere, and the biosphere. The following sections summarize problems and opportunities in each area. Appendixes A-D report on the areas in greater detail.

SOLAR-TERRESTRIAL SYSTEMS (see APPENDIX A)

Solar-terrestrial research is concerned with the interactions by which diverse forms of energy generated by the Sun influence the terrestrial environment and with the resulting complex interplay of physical and chemical processes in every element of the system comprising Sun and Earth (Figure 1). The Sun is a variable star. Transient outbursts, such as solar flares, and cyclic changes in solar magnetism, such as the 11- and 22-year variability of sunspots, remain to be understood. The size and figure of the Sun oscillate in a variety of modes. Understanding the processes causing these variations and the accompanying changes in solar output as they may affect the Earth will be a major preoccupation of solar research for a long time to come.

THE SOLAR-

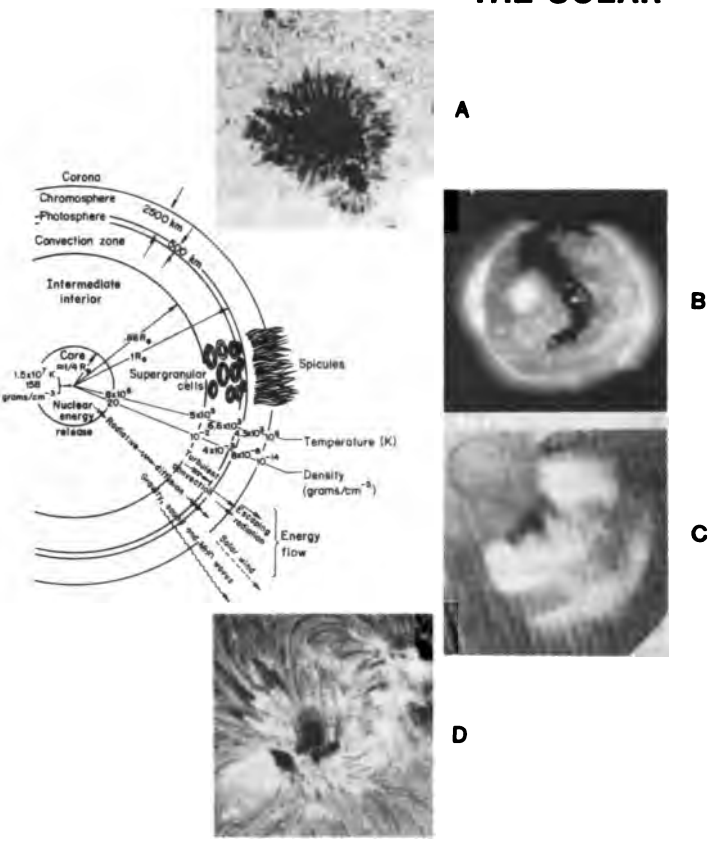
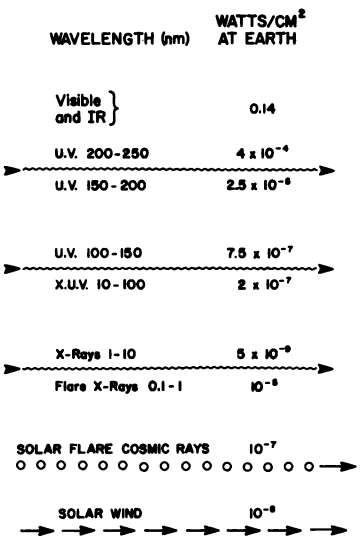


FIGURE 1 The solar-terrestrial system. Schematics On the left: Idealized solar properties, structures, and modes of outward energy flow. (After The Quiet Sun, E. G. Gibson, NASA Publication SP-303, 1973, Figure 2-3.) The dimensions of the concentric regions and the features are not to scale. Right center: Typical power fluxes of solar electromagnetic and particle radiation and of the solar wind, as measured at the earth's magnetosphere at far right. Photographic insets: A, A sunspot surrounded by the quiet photosphere with granulation. The field of view is several times the diameter of the earth. B, X-ray image of the sun showing a relatively cool, hence dark, coronal hole reaching from the north pole and winding across the solar equator toward the south pole. C, An image of the inner corona

TERRESTRIAL SYSTEM



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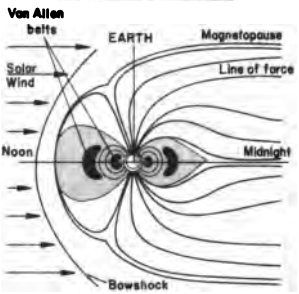


F

INTERPLANETARY

MEDIUM

taken with the NRL SOLWIND coronograph (satellite STP-78-1), on which is inset a monochromatic image of the solar disk (upper left corner). It shows an erupting cloud of plasma that has expanded to 4 million km (about 6 solar radii) in the 3 h following the onset of the flare surge shwon in the inset. D, A solar flare photographed in he monochromatic light of the red line of hydrogen, H-alpha. E, Far-ultra-violet airglow emission from atomic oxygen at high altitudes in the earth's atmosphere, photographed from the moon during the Apollo 16 mission. (NASA/NRL photograph.) F, Aurora photographed over College (near Fairbanks), Alaska. (Source: NRC Committee on Solar-Terrestrial Research, Solar-Terrestrial Research for the 1980's, National Academy Press, Washington, D.C., 1981, pp. 4-5)

Magnetospheric perturbations induced by episodic variations in the properties of the solar wind are coupled electrodynamically to the ionosphere, to regions deep in the atmosphere, and to the lithosphere. The processes involved in interactions of the solar wind with the magnetosphere, storage and transfer between regions of the magnetosphere, and coupling to the ionosphere and atmosphere are still poorly understood. Since the atmospheric effects may influence climate change, an understanding of these phenomena may be important to the entire geosphere-biosphere system.

The ionosphere (Figure 2) is a major sink of magnetospheric energy and exerts important feedback on the regions of the magnetosphere to which it is linked. Changes in the high-latitude ionosphere alter the global circulation and temperature structure of the thermosphere. The detailed nature of these interactions is not well understood, nor is the question of whether they affect, in a substantial way, the lower atmosphere. Variations in solar short-wavelength radiation and particle emission affect the composition and structure of the middle atmosphere, leading in extreme cases to possibly serious changes in atmospheric ozone. Such effects need to be further analyzed.

Finally, a thorough understanding of the photochemistry of the stratosphere and mesosphere is yet to be attained. Such knowledge would contribute importantly to assessment of the effects of trace gases such as nitrous oxide (formed partly by atmospheric electricity) and fluorocarbons and of variations in solar input on the ozone content of the middle atmosphere. Because of the importance of the ozone ultraviolet screen to the biosphere, these couplings have profound significance.

Key foci in solar-terrestrial research in the next few years include Origins of Plasmas in the Earth's Neighborhood (OPEN, see Appendix E), a program to examine the global flow of energy through the Earth's space environment above the upper atmosphere, and the planned Upper Atmosphere Research Satellite (UARS, see Appendix E), which are designed to improve our understanding of the chemistry and dynamics of the middle atmosphere and the flow of energy through this region.

OCEANS AND ATMOSPHERE (see APPENDIX B)

Over the last quarter century, our knowledge and understanding of the behavior of the atmosphere and ocean on a global scale have advanced impressively. Operationally oriented observing programs and special research-oriented field programs, in which space technology played a crucial role, have provided new insights into the dynamics and chemistry of the Earth's fluid envelope. This knowledge has provided the basis for the development of numerical models employed in weather prediction and simulation of the dynamics of the oceans and the variability of climate. Similar advances have been made in the understanding of our nearest star and its influence on our planet.

Three critical global multidisciplinary problems are perceived as major foci of attention in ocean-atmosphere research:

1. Dynamic and thermodynamic interactions between components of the climate system (Figure 3). The interactions between oceans, atmosphere, land, biosphere, and cryosphere maintain in delicate balance our climate and the natural productivity vital to life. A scientific strategy for the World Climate Research Program has been developed to address key problems employing emerging technological capabilities for observing the atmosphere, the Earth's surface, and the oceans. An early focus of activity will be the study of interaction between the tropical oceans and the global atmosphere as exemplified by the El Niño/Southern Oscillation phenomenon. In the longer term, the slow circulation and evolution of the world ocean will be addressed through a World Ocean Circulation Experiment.

2. The interactive processes of global chemistry, emphasizing the biogeochemical cycles of substances important to the stable maintenance of life and global climate. Over the past decade, we have come to regard the global atmosphere, oceans, solid Earth, and biota--including man--as an integrated chemical system. It is clear that this system is at present undergoing significant changes in the global and regional cycles of many substances. Many of these changes are coupled to human activity. Major problems include the following:

- Processes regulating the distribution of stratospheric ozone;
- The atmospheric hydrological cycle;

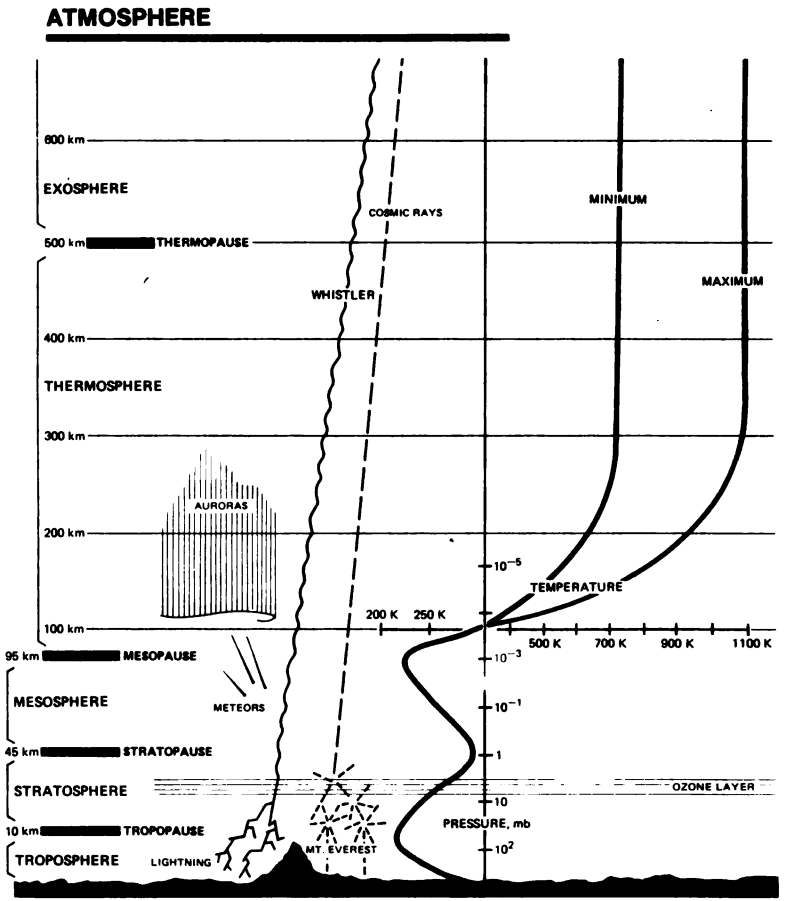
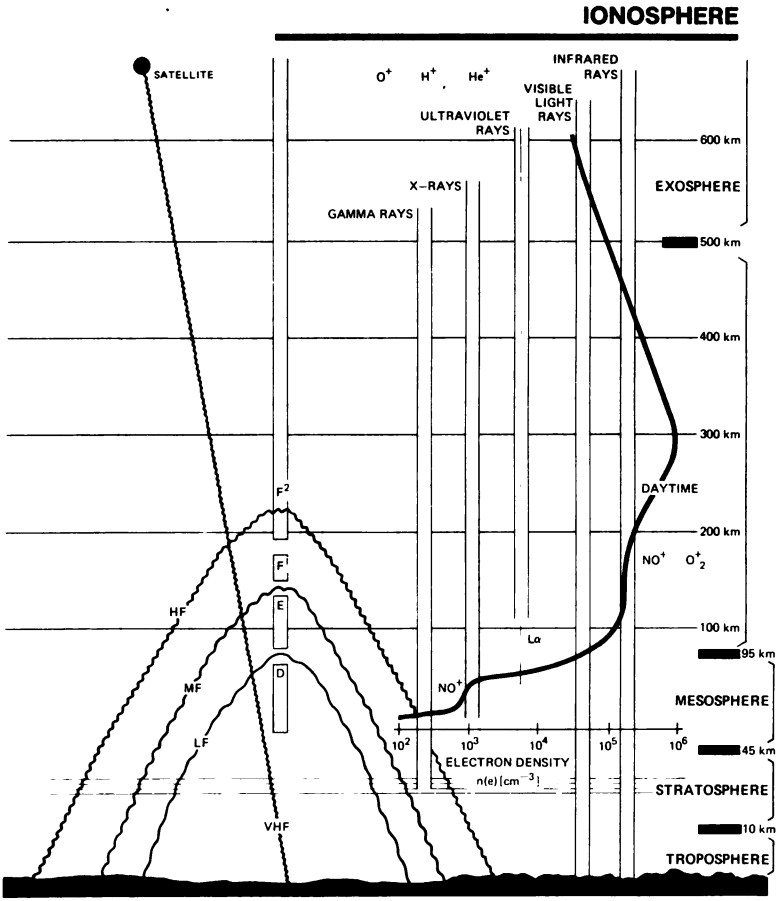


FIGURE 2 Ionized component of the atmosphere is produced by cosmic rays, gamma rays, x rays, and ultraviolet rays, which have maximum ionization rates in the D, E, F1, and F2 regions. Maximum concentration of electrons occurs in the F2 region, where the ionized component is about 1/1000 of the neutral-particle density. Shortwave radio signals are reflected from the ionosphere. X rays from solar flares produce radio blackout at an altitude of 60 to 75 km. Microwaves penetrate the ionosphere for satellite communications. Temperature inversions define the tropo-



pause, stratopause, and mesopause. The atmosphere is mixed, and the composition of major constituents is essentially constant up to the mesopause. Ozone concentrates in a thin layer in the stratosphere. At higher levels, molecules dissociate and lighter elements separate out by diffusion. Temperatures in the thermosphere maximize at sunspot maximum. (Source: NRC Committee on Solar-Terrestrial Research, Solar-Terrestrial Research for the 1980's, National Academy Press, Washington, D.C., 1981, pp. 20-21)

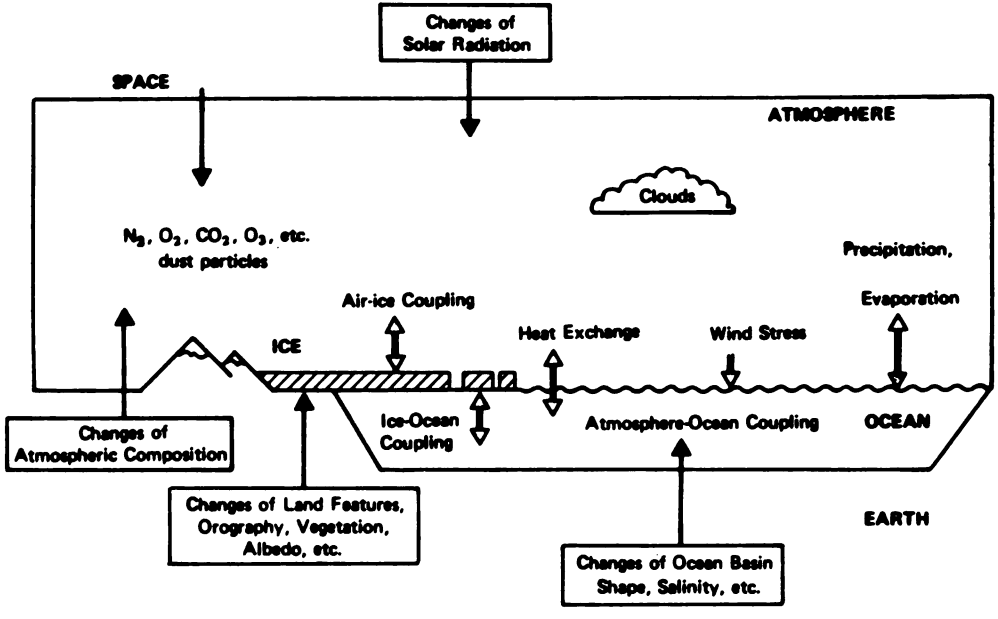


FIGURE 3 Schematic illustration of the components of the coupled atmosphere-ocean-ice-earth climatic system. The full arrows (--) are examples of external processes, and the open arrows (--) are examples of internal processes in climatic change. (Source: U.S. Committee for the Global Atmospheric Research Program, Understanding Climatic Change: A Program for Action, National Academy of Sciences, Washington, D.C., 1975, p. 14)

- The tropospheric distribution of oxidants;
- The chemistry of dry and wet deposition;
- The sources and sinks of radiatively important aerosols and gases;
- The ocean's role in biogeochemical cycles in terms of chemical, geological, and biological processes;
- Fluxes between ocean, atmosphere, lithosphere, and biosphere; and
- The role of land surface processes.

3. Sensitivity of the terrestrial system to solar variation. Solar variability on a broad range of time scales can have an impact on many terrestrial processes. Better understanding will require precise measurement of solar energy output and solar ultraviolet radiation. Information on past changes in insolation due to orbital changes should be exploited to understand the sensitivity of climate to solar variations.

Further advances in understanding the oceans and atmosphere will depend critically on the implementation of new technology for sustained data acquisition, processing, archiving, and dissemination to research users.

THE LITHOSPHERE (see APPENDIX C)

Development of the solid Earth has resulted from complex interactions of physical, chemical, and biological processes. The theory of plate tectonics has provided a framework into which we can fit diverse evidence from the solid-Earth sciences and a foundation upon which subsequent investigations of the evolution of the Earth are built.

The plate-tectonics model tells us that thermal convection must take place within the Earth, but we have not yet been able to characterize it. Related to this problem is the characterization of the chemical composition of mantle heterogeneities and their residence times. We do not yet have a clear picture of the various processes at plate boundaries nor quantitative estimates of subduction related recycling of materials and its effects on mantle evolution and basalt genesis (Figure 4). Associated with plate movements and processes are significant changes in paleogeography, paleooceanography, and paleoclimatology, the records of which remain to be fully reconstructed. We are beginning to understand geochemical cycling in the

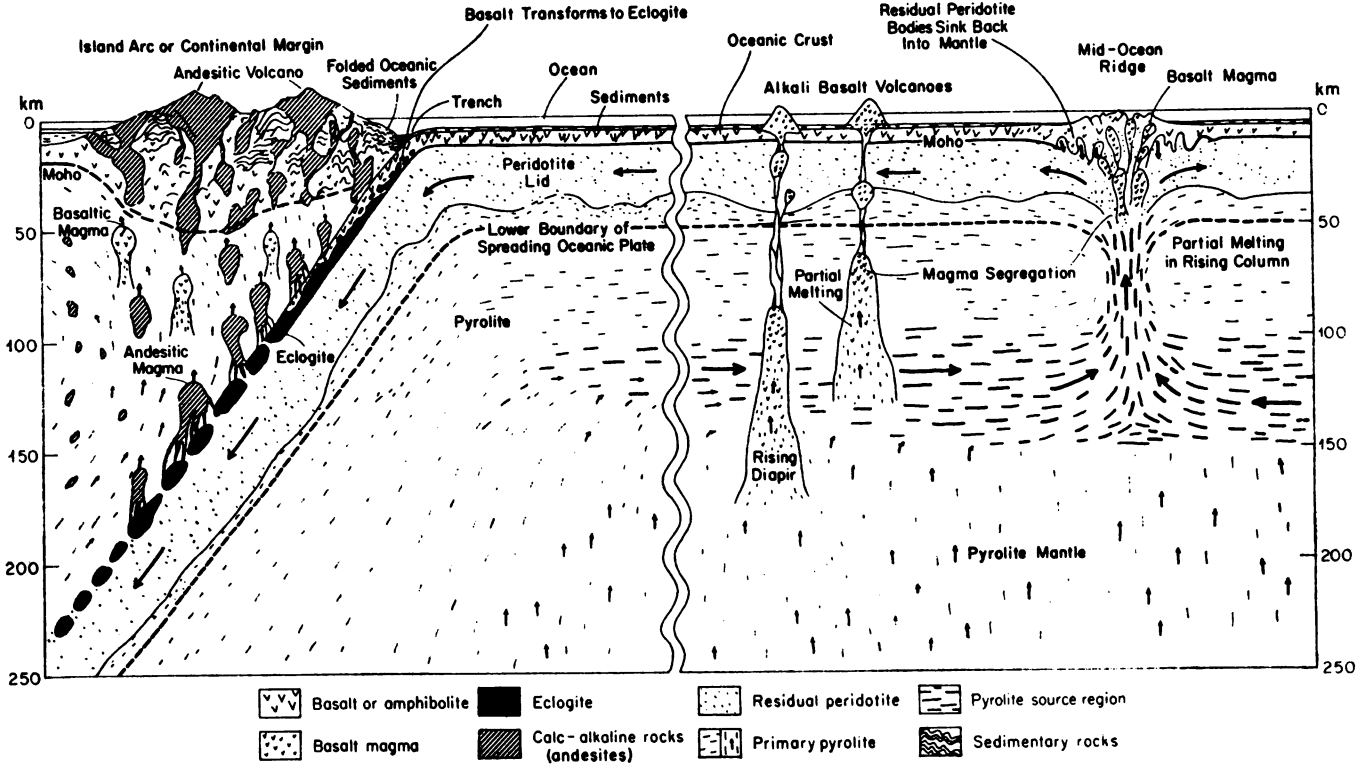


FIGURE 4 Modified version of oceanfloor spreading hypothesis. (A. E. Ringwood, in Geophysical Monograph 13, American Geophysical Union, Washington, D.C., 1969, p. 12)

mantle; for example, it is estimated that a volume of water equal to that of the entire ocean circulates through the oceanic crust every 8 million to 10 million years.

Much of what we infer about the early history of the Earth has come from comparative planetology. However, continental platforms and fold belts appear to be unique to the Earth, and except in the near surface, we know little about their structure and can only infer their origin and evolution. They hold the record of most of Earth's history, including that of life. The origin of life, the nature and rates of its evolution, and the nature of major changes and extinctions are among the principal challenges in the Earth sciences. An ocean and an atmosphere must have existed early in Earth history, but the degassing history of the Earth and the quantity of primordial components still being emitted remain to be determined. Activity around geothermal vents in the oceanfloor is offering a new perspective on possible origins of life.

The solid Earth, and especially the sedimentary stratum, on land and on the seafloor, holds the only record of past activity at or near the Earth's surface. This record includes chemical composition, climate variations, past organisms and their evolution, sea-level change, and biogeochemical information about life in the past. Much of this information is relevant to studies of cyclic phenomena and other variations of interest to researchers concerned with the biosphere, the hydrosphere, the atmosphere, and solar-terrestrial relationships. It appears possible that records of solar variability may be preserved in the sediments, that confirmation of hypothesized effects of short-term physical or biochemical events may be found, and that sources and sinks for chemical compounds can be established from the sedimentary record. Significant geological events have resulted from biological activity in the past, and, of course, our supplies of petroleum, coal, phosphate, and other resources are the result of interactions among the lithosphere, atmosphere, hydrosphere, and biosphere.

Many of the techniques and tools used for lithosphere studies are also utilized by or derived from other disciplines. Solar seismology uses methods of terrestrial seismologists. Marine biologists and physical oceanographers use acoustic tools developed by geophysicists, and seismologists are now developing tomographic techniques to study heterogeneity in the Earth's interior similar to those developed by physical oceanographers to

study internal variations in the oceans. The TOPEX mission, designed for physical oceanography, also promises important information for solid-Earth scientists, while the GRM mission of the geophysicists will provide information that will enhance the TOPEX data for oceanographers. It is obvious that the interchange of tools and techniques can enhance progress in all areas of investigation of the Earth.

THE BIOSPHERE (see APPENDIX D)

In thinking about global changes in the Earth, we must pay special attention to changes in living organisms--plants, animals, and bacteria--and their interaction with the oceans, the atmosphere, and the lithosphere. On a time scale of the next hundred years, the most important of these interactions will be those between the behavior of living organisms and climatic change.

Changes in the biosphere can bring about climatic change through the global cycles of the "greenhouse gases"--especially carbon dioxide, methane, and nitrous oxide; through changes in the regional and planetary albedo and other characteristics of the land surface; and through the effects of land vegetation on evapotranspiration and storage of water and on river runoff. Figure 5 shows the energy and water balance of the biosphere.

The influence of climatic change on the distribution and abundance of species has long been recognized, but more data are needed to understand better the effects of climatic change on the mass of the biota and on biological productivity. Several examples of feedback between biospheric and climatic change can be described. A diminution in the size of the land biosphere, caused by a rise in atmospheric temperature, will result in an increase in atmospheric CO_2 and hence in further warming. Similarly, because high biological productivity in ocean waters extracts CO_2 from the air and sequesters it in the ocean depths, changes in the intensity of ocean biological production caused by climatic change can result in large changes in atmospheric CO_2, with corresponding climatic effects.

The need for a multidisciplinary approach to study these problems can be illustrated by two questions: (1) How has the concentration of atmospheric carbon dioxide varied during past geologic times, and how will it vary in the future? (2) What is the cause of the present rapid rise in atmospheric methane?

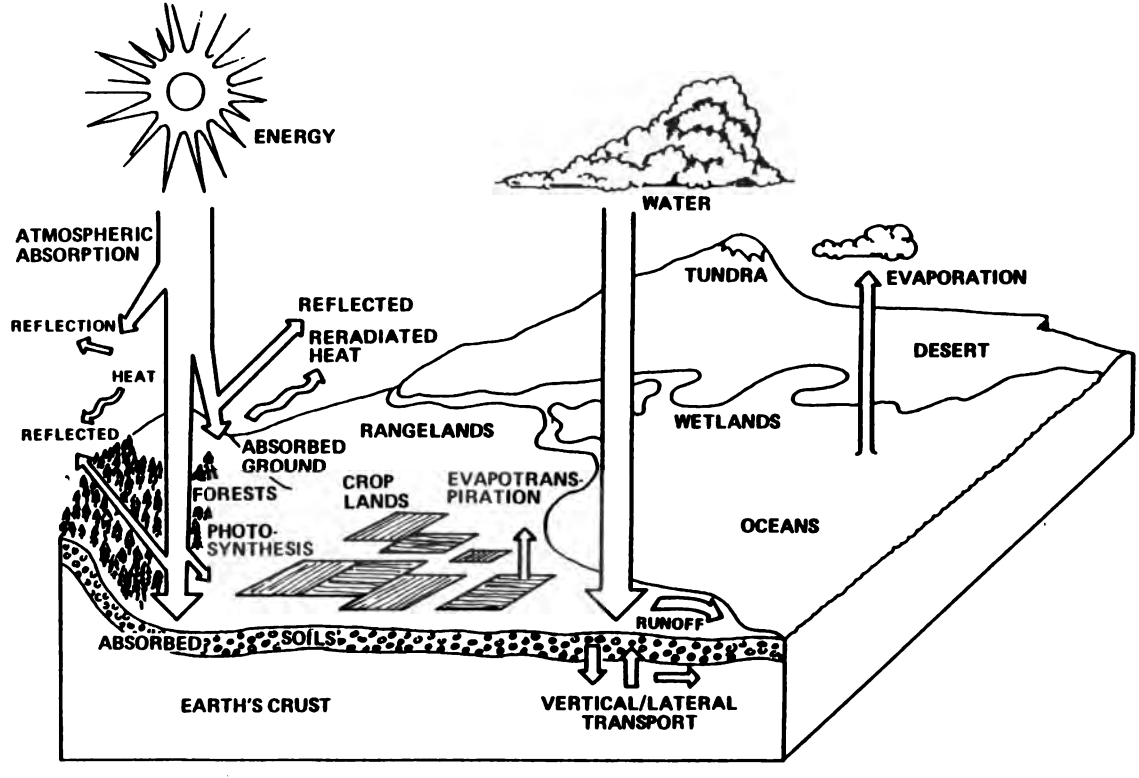


FIGURE 5 Energy/water balance. (Source: Land-Related Global Habitability Science Issues, NASA Tech. Memo. 85841, 1983, p. II.2-3)

Studies of oxygen isotopes in ocean sediments laid down during the Cretaceous period 60 million to 120 million years ago show that the temperatures of ocean waters at high latitudes were about 15 degrees warmer than at present. Were these high temperatures brought about by high concentrations of CO_2 in the atmosphere, and, if so, did the high atmospheric CO_2 result from a more rapid vertical ocean circulation, which prevented the sequestering of large quantities of carbon dioxide in the ocean depths?

Measurements of CO_2 in air trapped in ice cores from Greenland and Antarctica show that 10,000 to 20,000 years ago atmospheric CO_2 was much lower than at present, while 20,000 to 30,000 years ago CO_2 in the air fluctuated from approximately 175 to 300 ppm, apparently over relatively short times. Both of these conditions probably resulted from changes in oceanic biologic production, perhaps related, in the former case, to larger quantities of ocean nitrogen and phosphate, and, in the latter, to fluctuations in ocean biological production, which are poorly understood. The climatic effects of the relatively small variations in insolation resulting from the "Milankovitch" cycles in the Earth's orbital parameters may have been greatly amplified by fluctuations in the sources and sinks of phosphorous and nitrogen in the ocean, their consequences for ocean biological productivity, and, in turn, for atmospheric CO_2 levels. A major uncertainty about future atmospheric CO_2 concerns the question of whether forests will serve as a source or sink for carbon. CO_2 enhances photosynthetic production and reduces water stress on plants, but the significance of this effect in changing the size of the biosphere is conjectural.

Analyses of ice cores show that methane, one of the important greenhouse gases, was relatively constant during the 20,000 years before the seventeenth century and that it has doubled in concentration since that time. Its present rate of increase is apparently 1-2 percent per year. Is this increase related to changes in the biological sources of methane (i.e., symbiotic microorganisms in ruminant animals and termites, rice paddies, marshes, and swamps) or in the atmospheric sink? The latter depends on the atmospheric concentration of OH ions. Careful measurements of OH and studies of the size and productivity of methane sources over the next few decades should answer this intriguing question.

5

THE NEED FOR AN INTEGRATED APPROACH

From the preceding, it appears clear that a multi-disciplinary approach to many problems will be needed. An excellent example involving all four discipline groupings follows.

THE CO_2 QUESTION

It is reasonably well established that the observed continuing anthropogenic increase of atmospheric CO_2 will give rise to tropospheric warming and to shifts in global and regional climate over the next century. A quantitative assessment of the structure and degree of change requires an understanding of the dynamics of climate. The role that the oceans play is paramount in delaying and regionally modifying the climatic response to a given scenario of atmospheric CO_2 increase.

The diminishing reflectivity at the continental snow cover margin provides an important positive feedback, intensifying the high-latitude tropospheric warming. However, polar sea ice shields the fast-acting atmosphere from the slow-acting, and relatively warmer, sea below.

The inputs from the geological sciences enter in several ways. Effects of volcanic activity on atmospheric composition is one example--volcanic aerosols may partly counter or mask a greenhouse warming. A second important contribution from geological studies is climatic data for validating climate models in simulating extreme shifts of past climate. This also includes a knowledge of how other configurations of the continents may have influenced past climatic regimes.

Since the atmospheric response is primarily radiatively controlled, the balance of solar radiance and outgoing

infrared fluxes in determining the thermal structure of the atmosphere must be better understood. Recent results suggest that the climatic response to a doubling of CO_2, as measured by a surface temperature change, is qualitatively and quantitatively similar to that of a 2 percent increase in the solar constant.

Biogeochemical processes, of course, partially determine the partitioning of increased CO_2 production among the atmosphere, oceans, and biosphere. Determining the net atmospheric loading scenario thus involves an understanding of production, storage, transport, and transformations within and among the active terrestrial media. Changes in other greenhouse gases, such as water vapor, methane, nitrous oxide, and fluorocarbons, further complicate and increase the radiative response. Changes in their concentrations might obscure detection of an actual CO_2-induced signal, and secondary effects may be significant. A CO_2 increase would result in considerable stratospheric cooling, which, in turn, would decrease the rate of destruction of in situ O_3 and, therefore, lead to an increase in its concentration--which promotes still an additional alteration of the temperature and circulation of the stratosphere and affects the biosphere below.

Ultimately, the altered climate of the planet Earth, including the condition of the oceans, will have an impact on the biota--but how?

It is clear from this illustration that the prediction of future states of the regional and global climate resulting from anthropogenic CO_2 sources, and the resulting impact on humanity, will critically depend on a close integration of focused and coordinated research among the relevant disciplines.

A COMPREHENSIVE MONITORING SYSTEM

The interrelationships discussed in the Workshop indicate that many parameters in the geosphere-biosphere need to be monitored on a long-term basis and in a coordinated manner. Indeed, many of the same or similar observations, for example, on solar activity, vulcanism, and carbon fluxes, will be needed by more than one discipline group. In addition, simultaneous observation of physical, chemical, and biological processes, for example, in the oceans, could offer a rich new basis for scientific advance. Some of the needed observational techniques are now available

or have been demonstrated; others will be tested in programs under way or planned for the remainder of this decade. This provides the foundation for considering the design of an effective program of sustained observations beginning in the 1990s, which could achieve efficiencies and economies not possible with individual, uncoordinated activities.

COMMON OBSERVATION SYSTEMS

In either long-term monitoring or exploratory research of shorter duration, there are technological opportunities to use common observing platforms (e.g., satellites, buoys) or even sensors (e.g., multispectral imagers, solar and terrestrial radiation detectors, satelliteborne altimeters) to provide data required by several disciplines and studies. Coordination of the system and data specifications and the timing of observations may be feasible in many cases, thus providing increased scientific benefits from a fixed investment.

EXPLORING THE EARTH'S FUTURE FROM ITS PAST

A coordinated program of exploring the lithosphere and cryosphere not only would aid the solid-Earth sciences but would contribute to understanding climate change, biogeochemical cycles and the evolution of life on Earth, and the impact of solar variations. For example, analysis of lake and marine sediments can provide information on the history of climate and sea level, the biological record, and the geomagnetic field, which is also relevant to the past record of cosmic-ray flux.

OTHER COMMON FOCI

If we look at the totality of scientific questions and challenges discussed at the Workshop, a number of additional common thrusts emerge that tie together various disciplines:

- The dynamics of change: what are the characteristic rates and time scales of various processes--biospheric, solar, atmospheric, oceanic, and geological--and how do they interact?

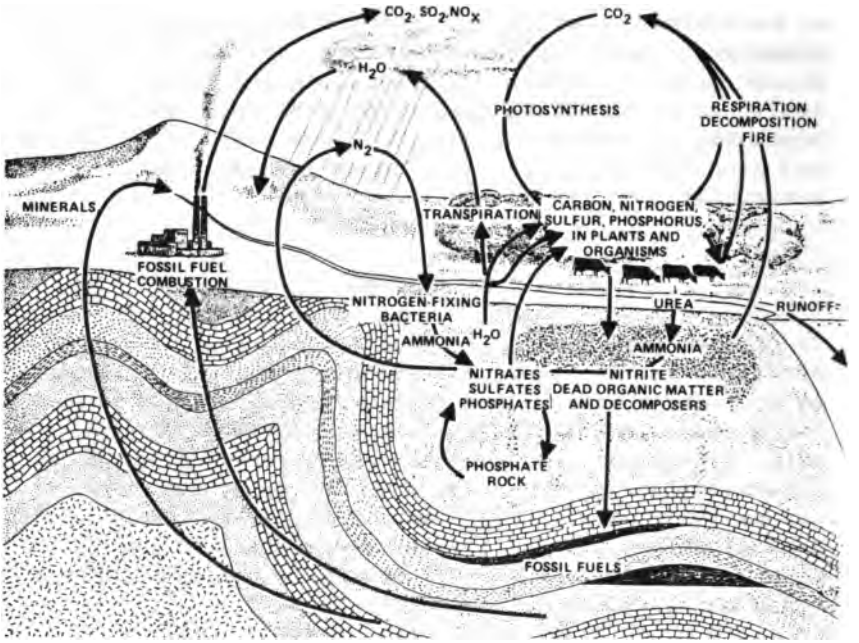


FIGURE 6 Schematic diagram of the major biogeochemical element cycles. The carbon cycle is the focus of material transfer through the biotic components of the cycles. Carbon is assimilated from the atmosphere by photosynthesis and released from pools of dead organic matter in the litter and soil by decomposition and fire. Nitrogen also has an important atmospheric component; however, the nitrogen cycle is quite complicated because of the role of microorganisms in fixing nitrogen from the atmosphere and transforming organic nitrogen to forms usable by plants. The cycles of other elements such as phosphorus do not involve significant atmospheric exchanges and operate primarily in the below ground component of terrestrial ecosystems. (Source: Land-Related Global Habitability Science Issues, NASA Tech. Memo. 85841, 1983, p. II.3-3)

- Biogeochemical cycles and global chemistry--the interaction with all media and their dynamics, the effects of solar variations, man's impact, the impact of the physical systems on the biological and vice-versa (Figure 6).
- Development of major integrative models of the geosphere and biosphere--for example, global climate models and models of radiative balance that treat albedo (cryosphere, snow cover, biomass, etc.), volcanic aerosols, and greenhouse gases; global ecosystem models; carbon cycle models; and plate tectonics models.

These thrusts call for multidisciplinary approaches and emphasize the need for international cooperation.

Appendix A

SOLAR-TERRESTRIAL SYSTEM

SUBSTANCE AND STATUS

Solar-terrestrial research is concerned with the processes by which diverse forms of energy generated by the Sun influence the terrestrial environment and with the resulting complex interplay of the physical-chemical processes in every element of the Sun-Earth system. The Sun provides much of the energy that drives atmospheric and oceanic circulation. Although most of the solar energy that is eventually deposited in our atmosphere (about 10^{11} MW) arrives in the form of visible light, variations in higher-energy radiations--ultraviolet, x-ray, and gamma--representing only a tiny fraction of the total power (about 10^{6} MW) have significant and highly variable effects on the terrestrial environment. The rate of transfer of other kinds of energy from the solar wind to the magnetosphere-ionosphere-atmosphere system is even smaller but is of so highly specialized a nature that its observable effects are far-reaching.

The Sun is a variable star. Sunspots and other manifestations of solar activity vary from day to day with clearly established cycles of 11 and 22 years. Episodic changes such as the Maunder Minimum (A.D. 1645-1715) modulate solar behavior on the 100-year and longer scale. Recent studies have shown that the total solar irradiance continuously varies owing to the blocking effect of sunspots. Flares produce outbursts of high-energy particles and electromagnetic radiation that perturb the upper atmosphere of the Earth. The size and figure of the Sun oscillate in a variety of modes that are only now beginning to be studied. The nature of the dynamical processes that drive these oscillations and how they bear

on internal structure and activity cycles are the objectives of solar studies in the coming decades.

Space extending out to the far reaches of our solar system, called the heliosphere, is occupied by a magnetized plasma, called the solar wind. Plasma-dynamical processes occurring in this medium can energize this plasma, and it also may respond to variations in the source of the magnetic field and the solar wind--the Sun itself. Understanding the processes that connect localized events on the Sun with the overall structure of the solar wind and dynamical processes in the heliosphere are the objectives of intensive investigations under way or planned.

The Earth is surrounded by a region of magnetized plasma called the magnetosphere, extending out to about 10 earth radii toward the Sun, where the solar wind encounters the Earth's magnetic field, and to hundreds of earth radii in the lee of the wind, where the plasma and the magnetic field are swept by the solar wind into a long comet-like magnetotail. Complex interactions connect the solar wind to the magnetosphere and energize the plasma and transfer it from one part of the magnetosphere to another. Eventually, some of the energetic particles in the magnetosphere enter the upper atmosphere of the Earth, particularly at high latitudes. The most spectacular manifestation of this interaction is the aurora. The mechanisms by which plasma is transferred and particles accelerated between the solar wind and the magnetosphere and between various storage regions in the magnetosphere are the principal objectives of magnetospheric research in the future.

The ionosphere, far from being a passive "viewing screen" of magnetospheric processes, plays an active role as a major sink of magnetospheric energy, exerts important feedback effects on the magnetospheric regions to which it is linked, and is the source of important perturbations that propagate to lower latitudes. In particular, energy and momentum input into the high-latitude ionosphere and atmosphere alters the global circulation and the temperature structure of the thermosphere, which are established mainly by solar heating. On the other hand, changes in the basic circulation pattern, caused by auroral activity or upward propagating waves from the lower atmosphere and thunderstorm electrical fields, may influence electrodynamic processes in the ionosphere and the magnetosphere. Pursuit of these relations requires coordinated research on a global scale.

The effects of the variability of both solar electromagnetic radiation and particle input on the structure of the middle atmosphere are poorly understood. Possible changes in chemical composition due to solar variability could perturb radiative and dynamic processes of the middle atmosphere, and this possibility needs to be explored. The middle atmosphere is also affected by exchange processes from below with the troposphere and above with the thermosphere, which must be considered in any attempt to understand the middle atmosphere. Perturbations (e.g., to ozone concentrations) resulting from natural or human activity could affect the Earth's climate.

KEY GLOBAL AND MULTIDISCIPLINARY PROBLEMS

1. Physics of Solar Variability and the 11- and 22-Year Cycles of Solar Activity. We know that the Sun varies and that these variations perturb the terrestrial environment. However, we cannot hope to predict such perturbations until we understand the detailed physical bases for solar variability itself. Fundamental questions of the physics of solar variations, such as flares and the 11- and 22-year cycles, have yet to be answered. We know that solar activity cycles originate beneath the visible surface of the Sun, in the convective zone where the solar dynamo couples magnetic fields and fluid motions. We are now on the verge of probing this key unexplored region through recently developed techniques of "solar seismology," involving the observation and interpretation of solar surface oscillations. Collecting and interpreting such data would involve activities on an international scale. Related investigations concerned with recovering the past solar (and climatic) history are of an interdisciplinary nature.

2. Response of the Magnetosphere to External Perturbations. The magnetosphere represents an important stage in the corpuscular energy flow from the Sun to the Earth. Many magnetospheric perturbations are coupled electrodynamically to deeper layers of the atmosphere and to the Earth's crust and affect large-scale man-made systems such as power lines, transoceanic cables, and pipelines. The relevant interaction processes between the source (the solar wind) and the magnetosphere, the energy storage and transfer processes, and the coupling between the magnetosphere and the ionosphere are still

poorly understood. An understanding of magnetospheric response to solar-wind variations (which are largely governed by solar activity) is essential for the study of possible effects on other components of the geosphere-biosphere. On the other hand, long-term, large-scale variations of the Earth's magnetic field are bound to change the magnetospheric configuration and all magnetospheric processes. An understanding of these secular changes will provide necessary input to the studies of the causes of drastic or catastrophic transitions in the geosphere-biosphere system.

3. Global Electric Circuit. The existence of a global electric circuit has been known for many years, yet we still do not understand the basic processes that drive and control the behavior of this system. According to the classical picture, the totality of thunderstorms acting together generate and maintain a potential difference of several hundred thousand volts between the highly conducting ionosphere and the surface of the Earth. In the fair-weather dissipative portion of the circuit, this potential difference drives a vertical electric current downward from the ionosphere to the ground. In order to advance our understanding of the main driving mechanism of this circuit, we need to establish the process responsible for charge separation in thunderclouds, the total current output from clouds into the global circuits, and the spatial distribution and frequency of cloud-to-cloud and cloud-to-ground lightning. The ionosphere is assumed to be an equipotential in current models. However, magnetospheric and atmospheric dynamo effects may influence this portion of the circuit in important ways. The distribution, size, and effect of the telluric current below thunderstorms also needs further study.

Lightning discharges may be significant to tropospheric chemistry, particularly through effects on nitrogen, but a great deal more work, both experimental and theoretical, needs to be carried out before its importance can be established.

4. To Understand the Chemistry of the Middle Atmosphere and Its Response to Transients. Early in the 1970s it was realized that products of man's activity, such as nitrogen oxides and chlorine compounds, might change the composition of the stratosphere and mesosphere in a serious way. Most important was their possible effect on ozone in this region of the atmosphere. Many of the gases involved, in addition to ozone, are optically

active in the infrared region and may affect the thermal structure and, consequently, the motions of the atmosphere.

The chemistry of the mesosphere and upper stratosphere is also affected by the absorption of short-wavelength and corpuscular radiation associated with transient solar events. The changes produced are potentially threatening to the health of organisms on the Earth's surface because of the reduced absorption of solar ultraviolet radiation by ozone. Thus, understanding the chemistry of this region and its response to transients is urgent and is now being intensively sought. There is a possibility that by the time an IGBP would begin, substantial progress will have been achieved. If not, it will continue to merit a major study effort.

5. Relationship of Solar Variability to Weather and Climate. The Sun provides almost all of the energy that drives atmospheric and ocean circulation. Significant variations in the inputs of solar energy to the Earth--or even small variations, if they are suitably amplified--are thus of primary interest in understanding the weather and the climate. A solid example is the influence of subtle changes in insolation in the pacing of the major Ice Ages through the Milankovitch mechanism of slow changes in Earth-orbit characteristics. Less understood is the apparent role of the 22-year magnetic cycle of the Sun in pacing a similar pattern of droughts in the western United States. A suitable interdisciplinary goal in this area is to understand the physical processes of interaction--chiefly in the upper and middle atmosphere--that allow solar variations to induce atmospheric changes. Such investigations seem best carried out through programs of measurement of solar inputs and in situ atmospheric changes, the development of theoretical mechanisms of response and coupling, and the utilization of analytical, atmospheric models in which quantitative mechanisms can be tested. Solar perturbations may or may not prove to be of importance in initiating short-term weather changes; they now seem to be important in terms of long-term climatic trends. In neither case is the extent of solar influence on atmospheric processes sufficiently known or delimited.

6. Advantages of International Participation

(a) Solar Variability. Studies of the Sun's interior (solar seismology) require periods of continuous, high-resolution observations of the solar surface that exceed what is available from dawn to dusk at any single

station. This observational need can be met by an elaborate, high-resolution Doppler telescope in Earth orbit or by a coordinated chain of observatories around the world. An optimum study would involve both. The observatory-chain approach clearly demands international cooperation.

The largely unread record of the past history of the Sun is preserved in various proxy data sources around the globe: in the tree-ring record of radiocarbon, in the radiocarbon and beryllium-10 histories of longer length preserved in ice and ocean cores, and perhaps in lake sediments and varves. Access to these sources of record clearly calls for international collaboration.

(b) Magnetospheric Response. To study magnetospheric response mechanisms requires systematic in situ measurements of solar-wind input and of the plasma, energetic particles, and waves in crucial near-Earth and distant regions of the magnetosphere. Spacecraft missions flown by different countries with observatory networks and chains covering extensive parts of the globe require tight coordination in terms of data-acquisition periods, physical parameter coverage, and data formatting to assure maximum scientific return. Well-equipped and internationally accessible data centers would increase the utility of data obtained by complex grid systems. In order to assure the possibility of participation in this research of countries without satellite-launching capabilities and countries with modest financial means, satellite and large-network data bases should be made available (after a suitable interval) in adequately equipped and supported repositories to the international scientific community.

(c) Global Electric Circuit. The electric circuit is global in extent and needs to be investigated on a global scale with both spaceborne and ground-based techniques. For example, ground-based observations by magnetic induction detectors are needed to establish the nature, frequency, and relative distribution of cloud-to-cloud and cloud-to-ground lightning on a global basis. Studying the magnitude and variability of atmospheric conductivity requires balloon-mounted detector systems that stay afloat a long time, perhaps crossing numerous national boundaries.

DATA NEEDS AND POWER OF NEW TECHNOLOGIES

Technological advances that benefit the study of solar variability and of the influence of solar variability on

climate are mostly in development of instrumentation for spacecraft and space platforms. Particularly promising are a new generation of Fourier tachometers that employ Doppler spectral techniques to record the patterns of radial oscillation of the solar surface with high spatial and temporal resolution.

New developments in optical systems will play a fundamental role in expanding the capabilities of remotely sensing magnetospheric processes from the ground and from space. Quantitative information on key parameters, such as the position of boundaries and the velocities and temperature of atmospheric constituents, can now be obtained on a continuing basis. New computer systems allow the handling of data on a massive scale, pattern recognition in data strings, and massive computer-interactive data analysis. Development of telemetry and communication systems and power sources allows the operation of large numbers of automatic stations in regions of difficult access and inclement climate. Finally, teleconferencing can improve the efficiency and effectiveness of cooperative scientific projects in which researchers are geographically dispersed.

Data Acquisition and Management. Organized programs are needed to facilitate the acquisition, exchange, coordination, and dissemination of data from ground-based, suborbital, and spaceborne observations on a global scale. Plans must be devised to analyze the data obtained from coordinated ground-based, suborbital, and space observations more efficiently and rapidly and to make these data readily available to the international scientific community.

Appendix B

OCEANS AND ATMOSPHERE

SUBSTANCE AND STATUS

In the last quarter century, prediction of atmospheric motions on the global scale has advanced from an art to a science. With global data and operational numerical models, forecasts of large-scale storm systems can be made out to several days, and skillful forecasts for more than a week have been demonstrated with research models. The atmosphere is an interactive turbulent fluid whose behavior is largely nonlinear; the increasing success of general circulation models (GCMs) and other tools in dealing with this fluid derives from a sound theoretical foundation, the availability of powerful computers, and better knowledge of the observed structure of the atmosphere, derived in large part from the observational experiments of the Global Atmospheric Research Program (GARP).

Equally remarkable advances have been made in our understanding of the ocean. Textbooks of a generation ago depicted the ocean in terms of a static system of sluggish basin-scale currents. Observational programs over the last two decades have revealed instead a complex dynamic system dominated by highly energetic small-scale features such as the mesoscale eddies. Numerical models have successfully simulated many of these phenomena. Now, major programs of observation and research are being designed on the scale of ocean basins and indeed the world ocean as a whole.

The lessons learned in development of atmospheric and ocean models can now be applied to a host of analogous problems of climate variability and change, involving all the complex and interlinked components of the climate system. We now have the ability to treat a whole hier-

archy of models, some including ocean-atmosphere coupling and other nonlinear relationships. We also have the capability of using satellite platforms to observe the changing state of the atmosphere, the oceans, and the external forces that act on them. Thus, many interactions of our ever-changing Earth involving the Sun, atmosphere, land, oceans, ice caps, crust, and biota are becoming increasingly accessible to observation and modeling on a global scale.

In looking to the future we see two major research challenges--global climate studies and global chemistry--that will deal with the interlinked ocean-atmosphere system and will require strong interactions between several disciplines and cooperation among many nations to ensure success.

A decade of intensive planning has led to a soundly conceived strategy for a WMO/ICSU World Climate Research Program (WCRP). This program seeks to improve our understanding of climate variability and change in terms of three time scales:

1. From a few weeks to a few months, a range in which the oceanic boundary condition may be regarded as constant.
2. Up to a few years, requiring the interaction of the upper layers of the ocean and the land surface.
3. Long-term climate sensitivity to external perturbation, in which the entire climate system must be considered interactively.

Programs have been developed to address a number of the principal problems in modeling key processes in the climate system, e.g., cloudiness-radiation interactions, oceanic-atmospheric coupling, and land-surface processes. Promising capabilities have been demonstrated to observe wind stress, surface topography, surface temperature, and fluxes of heat and moisture over the oceans, and possibilities also exist for observing the ocean's internal structure through acoustic tomography.

A problem to be addressed early in the course of the World Climate Research Program is the phenomenon of El Niño and the Southern Oscillation, perhaps the largest signal in short-term climatic variability in the month to interannual time frame. Plans for a major decade-long program of field observations and supporting research are now being developed nationally and internationally under the name of TOGA (interannual variability of the Tropical Ocean and Global Atmosphere).

Challenging problems in climate research remain on decadal and longer time scales. The long-term circulation of the world ocean and the processes of formation of water masses are fundamental to determining the response of climate to human influences. These problems will be studied in a World Ocean Circulation Experiment now in its embryonic state. The atmospheric concentrations of trace substances that absorb, emit, scatter, and reflect radiation also interact with the components of the climate system in complex ways that must be more accurately described and estimated. Moreover, the impact of changing climate on the biosphere is only crudely understood at present and must be better assessed as a guide to research, prevention of harmful effects, or adaptation to change. In addressing these longer time scales it has become apparent that we must radically improve our knowledge of the chemical aspects of the climate system.

Over the past decade, there has been a revolution in our appreciation of the chemistry of the fluid portions of the Earth. We now regard the global atmosphere and oceans as an integrated chemical system with continental- and global-scale connections and recognize that this fluid-chemical system reacts in critically important ways with the solid Earth (including the ice caps) and the biota (including mankind). Of equal importance, we now know that the chemistry of the global system is being demonstrably perturbed; in particular, there are clear signals of altered fluxes in the global and/or regional cycles of carbon, nitrogen, sulfur, phosphorus, and water substance and in the atmospheric budgets of several radiatively important gases.

Perturbations to the carbon cycle are manifest through readily observable changes in the concentrations of atmospheric CO_2 and CH_4, both radiatively important gases. Similarly, perturbations to the nitrogen cycle are evidenced by changes in the concentrations of atmospheric N_2O (another radiatively important gas) and other nitrogen oxides. Fossil-fuel combustion has led to enhanced acidity and sulfate concentrations in precipitation and to an additional burden of sulfate aerosol in Arctic haze. It is difficult to identify a major river or estuary that has not been affected by the addition of anthropogenic phosphate. Widespread deforestation, irrigation in semiarid regions, and overgrazing have led to radical changes in the rates of exchange of H_2O between land and atmosphere in the affected areas. Anthropogenic releases of several halocarbons have

produced significant upward trends in the atmospheric concentrations of these halocarbons and generated widespread concern about their potential effects on stratospheric O_3 and climate.

KEY GLOBAL AND MULTIDISCIPLINARY PROBLEMS

1. Dynamic and thermodynamic interactions between components of the climate system: oceans, atmosphere, land, biosphere, and cryosphere. The Earth's weather and overall climatic state reflect a complex flow of mass, momentum, energy, and chemical species between the hydrosphere, cryosphere, atmosphere, and oceans. These storage, transmission, and transformation processes maintain a delicate balance that makes the Earth habitable and determines the agricultural and marine productivity of the planet. Slight changes in the interconnecting links of this system can lead to profound effects. For example, the El Niño-Southern Oscillation phenomenon is linked to changes in marine productivity, monsoon rainfall, and midlatitude weather.

A central problem for the future is to develop adequate knowledge and understanding of the coupled dynamics of the atmosphere and ocean as a basis for modeling their complex interactions.

Orderly, comprehensive, and well-integrated planning is under way in the WMO/ICSU World Climate Research Program (WCRP). In view of the advanced state of effort in the area of climate, we will not dwell further on these programs here except to emphasize that full implementation of the WCRP has yet to occur.

2. Interactive role of global chemistry, emphasizing biogeochemical cycles (carbon, nitrogen, sulfur, phosphorous, H_2O) and radiatively active gases and aerosols. Our understanding of global chemistry, in particular the biogeochemical cycles and radiatively active gases and aerosols, has now reached a critical stage in its development. There are observations that defy easy and immediate interpretation and a suite of hypotheses demanding carefully conceived measurements over the globe.

Of the elements of the Earth's fluid-chemical system, our understanding of the stratosphere is relatively mature and priorities are readily defined. The primary chemical problem in stratospheric research is to understand the processes that regulate the abundance and

distribution of O_3 as it may affect the intensity of ultraviolet radiation at the Earth's surface and may influence regional and global climate.

Our understanding of the chemistry of the troposphere is in a relatively primitive stage. At present we can identify at least four major problems for global tropospheric chemistry: quantitative understanding of the atmospheric hydrological cycle; definition of the processes that regulate the distribution and abundance of oxidants (notably OH, O_3, SO_2, and NO_2); definition of the factors that influence the chemistry of dry and wet deposition; and quantitative identification of the sources, sinks, and temporal trends of aerosols and of radiatively important gases (CO_2, NO_2, CH_4, NH_3, H_2O, N_2O, halocarbons).

Like tropospheric chemistry, the area of oceanic chemistry is at a juvenile stage. We must quantify the role of the ocean in the biogeochemical cycles of C, N, P, and S and in the global budgets of a broad suite of radiatively and/or chemically important gases including N_2O, CH_4, CO_2, H_2S, and $(CH_3)_2S$. The roles of sediment formation, cycling of ocean water at ocean ridges, and biological processes in the chemistry of the oceans need further exploration.

There are also readily identifiable goals concerning the interaction of the ocean-atmosphere system with the lithosphere and biosphere. Subduction of sediments, oceanic ridge emanations, and volcanoes play important parts in the global balance of volatile elements and aerosols over a very wide range of time scales. Rivers, estuaries, and coastal zones provide the major coupling between the land surface and ocean. An important problem in riverine research is to determine the fluxes of H_2O, C, N, P, and sediment from land to ocean and to elucidate the factors controlling these fluxes. Research on coastal systems should focus on coastal marine productivity and the transfer of important chemical species to the open ocean.

The biosphere is an integral part of the global chemical system. A central problem in global chemistry is to elucidate the nature of the physical, chemical, and biological processes regulating release and uptake of important chemical compounds by the biosphere and to clarify the response of the biosphere to an alteration in either the physical or chemical state of the atmosphere. Early emphasis should be directed to the study of gases such as CO_2, CH_4, N_2O, NO_x and SO_x, whose concentrations are known to be changing significantly.

3. Sensitivity of the terrestrial system to solar variations. Solar radiation drives the terrestrial system, and solar variability on a broad range of time scales can have substantial impact on physical, chemical, and biological processes. Understanding the effects of solar variability requires accurate measurements of the solar output to test physical mechanisms. Key observations required for future research on Sun-Earth relationships include the following:

(a) High-precision measurement of solar energy output from satellites has shown changes of a few parts per thousand over days and months. Changes of this magnitude occur over time scales of several years or decades could conceivably be a major cause of multiyear climate variability. We must continue accurate monitoring of solar irradiance over a full solar magnetic cycle.

(b) Solar ultraviolet radiation controls the production and destruction of important stratospheric and mesospheric chemical species. Changes in the solar ultraviolet spectral distribution can therefore change the vertical temperature and species profiles in this region of the atmosphere, which in turn modify stratospheric circulation. Large intensity variations in the ultraviolet have been measured over short time periods. Such measurements need to be maintained with satisfactory calibration over decadal time periods.

(c) The Milankovitch effect could provide an invaluable test of the sensitivity of the climate system to solar changes and verify our ability to understand and model such changes. Analysis of long-term Earth orbital changes and associated paleoclimatic records deserves high priority.

DATA NEEDS AND THE POWER OF NEW TECHNOLOGY

Worldwide observations of the ocean and atmosphere have a long history, based largely on practical requirements. Today, operational global ground- and space-based systems exist for some atmospheric and oceanic observations. Although these networks are far from adequate for research purposes, the fundamental prerequisite for future progress is to continue and build on the existing global observing system. The 1979-1980 Global Weather Experiment demonstrated the capabilities for global observations of greatly improved resolution and accuracy, and research is

under way to assess the implications of possible improvements in the operational observing systems.

In order to address effectively the problems of global climate, atmospheric-oceanic composition and chemistry, and relationships of these systems to solar variations, sustained global observations of many variables will be required. The magnitude and scope of the required effort demands close international coordination and full exploitation of technological opportunities for both remote and in situ observations. Of particular importance are global observations of the ocean and of atmospheric composition.

The observational programs of the past have yielded an immense volume of data relevant to the problems of global change. Future programs will produce still further deluges of data. Meaningful and effective research will be possible only if scientists have ready access to these data in forms appropriate to their needs. The collection, processing, archiving, and dissemination of such data sets is an immense but tractable task. The use of new communication and computer technologies and strong international collaboration will be essential.

Appendix C

THE LITHOSPHERE

SUBSTANCE AND STATUS

In solid-Earth sciences, conceptual advances of the last two decades, technological developments, and strong intellectual ferment form a sound basis for a concentrated global attack on some of the great problems of science. The nature of the efforts required is stimulating in its diversity--ranging from theoretical studies using sophisticated models of the dynamics of the interior to physically taxing geological and geophysical field studies designed to probe huge parts of the Earth that are essentially unexplored and unknown.

Solid-Earth scientists in North America have recently begun to bring together diverse bits of information through programs such as the Decade of North American Geology (DNAG), which involves Canada, Mexico, the United States, all countries of Central America, Iceland, and Greenland. The results have drawn attention to gaps in knowledge of the Earth left by uncoordinated national efforts and the need for coordination on a still larger international scale.

The theory of plate tectonics provides a framework within which sharply focused questions can be asked about how the solid Earth is shaped and is evolving. For example, recognition of relative plate movements answered the question of whether thermally driven convection occurs in the mantle; current investigations center on the pattern, scale, and speed of flow in the mantle. The dual approach to the problem--theoretical models of convection that include a temperature-dependent rheology and observational programs that include geophysical probing of the asthenosphere and surface expressions of convective flow--is rapidly providing new insight into

the upper 700 km of the Earth and how processes in this zone relate to the kinematics and stresses of plate movements.

There is much debate regarding the convection: is it mantle-wide and at a scale comparable with plate dimensions, or is it at two scales with convective overturn in cells in the upper mantle measuring hundreds of kilometers across, with independent convection in the lower mantle of an unknown nature? The cause of hot spots (intraplate thermal welts) is a key to this debate; many scientists suggest that they are associated with plumes of material escaping from the deep mantle.

Changes in pressure and temperature of material within the Earth, caused by the physical process of convection, are responsible for the chemical differentiation of the Earth into distinct chemical reservoirs. The core, mantle, and crust were produced by gravitative separation of molten fractions produced by partial melting of the material that accreted to form the Earth. The atmosphere and hydrosphere separated from the gases boiling out from this molten material. Volcanic activity has contributed to evolution of the crust, atmosphere, and hydrosphere throughout the 4.5 billion years of geological time. We have much to learn about the physics and chemistry of all of these processes.

The fluid envelopes of atmosphere and hydrosphere have interacted with near-surface rocks to produce and to recycle the veneer of sedimentary rocks. The organic compounds of the biosphere (generated by photosynthesis) modify many chemical reactions among rocks and fluids and contribute both solid and fluid components to sedimentary rocks. The biosphere has exerted a strong influence on the chemical evolution of both hydrosphere and atmosphere, in ways that have not been clearly distinguished. The sedimentary rocks contain evidence for these changes, and much of the evidence awaits discovery.

An intellectual challenge of the first order is to understand the factors involved in the origin and evolution of plant and animal life. The recent discovery of submarine oases associated with mineral-laden hot springs emerging from the oceanfloor in these environments is causing re-evaluation of our previous concepts of the origin of life. There is current controversy regarding evolutionary rates as determined from the geological record: Is evolution a basically gradual process, or does it occur in short bursts that punctuate long periods of relative inactivity? This controversy has been

stimulated by the suggestion that significant changes in number and type of species has been caused by large singular events such as the impact of extraterrestrial objects on the Earth.

KEY GLOBAL AND MULTIDISCIPLINARY PROBLEMS

1. Physical Evolution

Some of the great questions of geology are also the simplest. Why are there continents? How have the continents evolved to their present configuration? What is their configuration at depth?

The geology of the Earth's surface is focused on the movement of tectonic plates and their origins. There are two major avenues of research in this area. One is reconstruction of geographical positions of oceans and continental fragments in the past. This task has been accomplished in a relatively persuasive way back to the Permian, but for more ancient times geologists must depend on increasingly ambiguous data about paleo-pole positions and the paleoenvironment as revealed by fossils and rocks. Determination of paleogeography sets the context for paleo-oceanography, paleoclimatology, and biological evolution.

The second major avenue of research on physical evolution of the lithosphere is directed toward basin formation, vulcanism, and mountain building, which occur primarily at the boundaries of lithospheric plates, and secondary sites over hot spots. Understanding orogeny, subsidence, metamorphism, and magmatism is essential to interpreting continental rocks.

Over the first 2 billion to 3 billion years of Earth history, theory of plate tectonics fails to explain various phenomena. The suggestion has been made that during early Earth history the forces that shaped the structure and composition of continents resulted from a quite different surface expression of convection, a convection without large well-defined lithospheric plates. Archean geologists are showing progress with this question, which is likely to remain important for some time.

Insights into questions of physical evolution of the Earth are almost certain to be found through theoretical development matched to a program of exploration of the entire continental crust throughout the world using

standard geophysical crustal exploration techniques, such as gravity, magnetism, electromagnetics, seismic refraction, and techniques such as seismic reflection and drilling borrowed from the petroleum industry, where their application is largely confined to study of shallow sedimentary basins. The goal for such studies should be a comprehensive network of surveys spanning the major geological features of all continents.

Important evidence is also to be found in the sedimentary records of the numerous basins located on all continents and in the deep and shallow seas. The physical, chemical, and biological nature of sediments, as well as their sequence and configuration, provide information on the history of climate and sea level, on past episodes of glaciation, and on the ancient geological environments in which the sediments were deposited.

Sediments contain most of the world's oil and gas reserves and some of its mineral resources. Other mineral resources are found in the crystalline rocks of the crust. Improving inventories of mineral resources is a continuing objective of economic importance; progress requires a basic understanding of the processes that concentrate minerals and the geological circumstances that foster the processes.

Sediments also provide a record of past fluctuation of the geomagnetic field, information that is relevant to the cosmic-ray flux, and to biological history.

2. Chemical Evolution

In a general sense, we can view the entire system of atmosphere, hydrosphere, biosphere, and rock mass on the outer parts of the Earth as a chemical recycling system. The fluid envelopes of the Earth were derived from rocks and have experienced continuous interaction and reaction with the near-surface rocks and recycling through the crust and upper mantle. These processes are associated with enormous fluxes of H_2O, CO_2, and other elements. The chemistry of materials at and near the boundaries between fluid and solid layers is monitored and modified significantly by the biosphere, and components of the biopshere are incorporated into sedimentary rocks. Our knowledge of these chemical cycles is at a rudimentary level, because of problems of determining the major sources and sinks for many species. Inputs and outputs of the atmosphere-hydrosphere should be quantitatively

determined in terms of fluxes and time constants (transport coefficients).

Understanding the geochemistry and rates of circulation and exchange of the hydrosphere with the oceanic crust and with the upper mantle represents a major intellectual challenge for scientists in several areas. The chemical evolution of the ocean, once thought to be controlled largely by biogenic and sediment-water reactions, is now known to be dominated by the flux of ocean water through deep, geothermally heated basaltic ocean crust near ridge-spreading centers.

It is estimated that a volume of water equal to that of the entire ocean circulates through the oceanic crust every 8 million to 10 million years. Some of the ocean water and its dissolved components become fixed in the oceanic crust. Subduction of the oceanic crust transports H_2O and CO_2 from the hydrosphere into the Earth's mantle down to depths of at least 100 km. Some of these volatile components are transported back to the surface dissolved in lavas, but an unknown fraction may be trapped for long-term storage in the mantle. It appears to take abut 500 million to 1 billion years for a mass of water corresponding to that of the present ocean to be cycled through the mantle in subduction zones.

Results from isotope geochemistry suggest that there are at least two types of chemical reservoir in the mantle, which have remained chemically distinct, and presumably isolated from each other, for 1 billion to 2 billion years. One reservoir provides the basalts sampled at ocean ridges; all other basalts are derived from different types of mantle reservoirs that appear to have been contaminated, or enriched, by elements characteristic of the crust. The hydrosphere may have participated indirectly in this contamination process. Further exploration of reservoirs and long-term exchanges offers promising opportunities.

3. Evolution of Life

Many life forms have evolved and disappeared during the Earth's history, sometimes rapidly and sometimes more gradually in response to changing conditions. The topic of long-term evolution of life involves multidisciplinary research into environmental conditions throughout the Earth's history, climatic changes, changes in solar radiation and cosmic-ray flux, ever-changing conditions

on the Earth's surface such as the extent and nature of seas and land masses, composition and circulation of the hydrosphere and atmosphere, and the response of biological processes to these changes. Paleontologists are seeking evidence of the nature of evolution of the atmosphere and ocean during the history of the Earth, patterns of climate at various times during the past billion years, previous global physical and biological geographies, as well as effects of large, short-term events.

Many of the conclusions about response of organisms to environmental stress come from studies of forms that lived in low to middle latitudes. If land plants or phytoplankton at high latitudes are especially sensitive to small changes in solar input, significant new opportunities may exist for seeking evidence for solar variability in the past in these regions.

DATA NEEDS AND THE POWER OF NEW TECHNOLOGIES

Advances in our understanding of the solid Earth have usually followed the development of new technologies for examining it. In some instances, such as development of submersibles or application of the drill, the advances come through access. In others, such as new acoustic techniques, either on land or at sea, the advances are the result of more detailed and more coherent views of the Earth's interior or its physical properties. Satellite observations provide us with a global view of many phenomena and permit global synoptic observations of changes. In addition, satellite positioning systems are beginning to permit us to measure actual motions of the continents and are making possible measurements at sea that could not be made earlier. Geochemical and isotopic instrumentation permits accurate measurements on very small samples, leading to better understanding of geochemical reservoirs and fluxes. High-pressure technology has advanced to the point that we can now study Earth materials under conditions approaching those in the Earth's core.

Computer technology has opened up a new phase of geophysical exploration. The ability to analyze complex signals from hundreds of sensors and display them as maps and sections almost as soon as the information is received has increased manyfold the power of seismic, magnetic, and gravitational instruments. In addition, these displays can be transformed and filtered in an almost

infinite number of ways that enhance features of the signals of greatest interest. This revolution spans the earth sciences and is rapidly leading to a new era of exploration and discovery.

Often, these new technologies, developed for one purpose or discipline, have benefits to others. Satellites carrying altimeters, such as Seasat, have yielded results of surprising detail. The proposed TOPEX mission, designed for physical oceanography, promises to provide exciting new data for solid-Earth geophysicists, while GRM, designed for the solid-Earth geophysicists, will provide data that will enhance the value of the TOPEX data for the oceanographers. Deep towed instruments and submersibles used to examine the geology, geochemistry, and geophysics of the ocean rifts uncovered a new type of ecosystem based on chemosynthesis rather than photosynthesis. Seismic and drilling techniques developed in the search for petroleum are ready tools for the scientific exploration of the Earth's interior.

These new technologies are rarely inexpensive and exploitation of their abilities requires planning, coordination, and a well-organized rationale for their use.

Appendix D

THE BIOSPHERE

SUBSTANCE AND STATUS

The biosphere is the planetary system that includes and sustains life, and its study involves participation from all the disciplines of the natural sciences. During the last few decades, studies of the biosphere have led to large-scale multidisciplinary approaches, including global ecosystem modeling, in which a major effort has focused on assessing the pathways and rates of exchange for the primary constituents of living organisms--carbon, nitrogen, phosphorus, sulfur, hydrogen, and oxygen. This research has been fruitful, yielding insights into both the long-range evolution of the Earth and potential effects of recent and ongoing changes on ecosystems, the atmosphere, and climate brought about by human activities. Nevertheless, our current understanding of the interactions remains incomplete.

Improved understanding of the biosphere and its relation to the other great domains of the Earth has a special urgency. This urgency arises in large part because of the potential significance for humans and other species of changes that we see in prospect. It arises additionally because of the rapidity with which changes are taking place. For example, changes in the area and character of forests, by far the most important terrestrial biome with respect to the carbon cycle, have occurred at dramatic rates over the last 100 years. Each year that goes by without careful assessment is a regrettable loss. Delay in obtaining understanding of the dynamics of the biosphere would be unfortunate.

The status of research on the biosphere is, however, encouraging in several respects. Rapid progress is

occurring in numerous areas, for example, the carbon cycle, primary productivity of the oceans, and ecosystem modeling. Multidisciplinary cooperation has been increasing, and young scientists are developing careers around the many exciting problems in the area. At the same time, limitations and obstacles have become apparent. The need for increased cooperation and research across disciplinary boundaries is obvious. This need is particularly great with respect to researchers focusing on the oceans, the atmosphere, and climate but exists in other areas as well. Reconstructing the longer-term history of the biosphere involves cooperation with experts on solar behavior to clarify the influence of the Sun on the primeval Earth and with Earth scientists who find the record of the past generations of biota written in the rocks and recent sediments. The need for better data on which to build understanding is essential. To illustrate, assessments of the extent and carbon content of forests and their rates of change or the production of methane by the biota rest on disappointingly scant samples of data. The following section describes some major research questions involving the biosphere, where a program of multidisciplinary, international cooperation is likely to yield intellectual and societal rewards.

KEY GLOBAL AND MULTIDISCIPLINARY PROBLEMS

1. To what extent do processes in the biosphere determine global and regional climatic changes? Here we are concerned with (a) fluctuations in atmospheric concentrations of "greenhouse" gases, mainly carbon dioxide, methane, and nitrous oxide, resulting from biological processes on land and in the ocean, together with changes in fluxes from the Earth's interior; (b) changes in regional and planetary energy balance caused by changes in the vegetative cover on land areas; and (c) effects of land vegetation on the hydrological cycle, primarily by influencing the amount of evapotranspiration and stream run-off.

Over longer time periods, the biological processes may amplify the climatic effects of the Milankovitch cycles in the Earth's orbit and pole of rotation. Does this occur? Alternatively, do substantial biospheric effects occur on decadal or 100-year time scales or only over longer time periods?

(a) Greenhouse gases. Prior to the effects of human activities, what combinations of chemical and physical processes brought about changes in the atmospheric concentration of carbon dioxide, and over what time scale did these changes occur? For example, changes of biological production in subsurface ocean waters and in the rates of transfer of organic matter to deep water alter the partitioning of carbon dioxide between ocean and atmosphere. What are the relative effects of changes of ocean quantities of phosphorus and fixed nitrogen and of the rates of vertical circulation of these nutrients in determining biological productivity? To what extent are rates of transfer of carbon from the atmosphere and the surface ocean to the deep water determined by seasonal fluctuations in phytoplankton and zooplankton production, such as the early spring phytoplankton bloom in the northwestern North Atlantic?

In addition to the longer-term variations in the concentration of important greenhouse gases there are important contemporary perturbations in some of these concentrations. For instance, the current transient behavior of CO_2 provides a unique opportunity to gain insight into the functioning of the global carbon cycle, through which to develop a deeper appreciation for the functioning of the biosphere as an integrated planetary system. The change observed in CO_2 results from a combination of influences: release of CO_2 associated with combustion of fossil and biospheric carbon; possible alteration of carbon stored in the biosphere; possible modification of carbon stored in soils and sediments; and a probable change in the rate at which carbon is taken up by the ocean.

In addition to CO_2, the concentration of other important greenhouse gases, such as methane and nitrous oxide, are changing, and yet we do not know the causes of these changes or their future course. We need to know what is the relative importance of different sources of methane, i.e., symbiotic micro organisms in ruminant animals and termites, rice paddies, marshes and swamps, continental slope sediments, and geothermal reduction of organic compounds in sediments above rift zones on the seafloor. What biological processes in the ocean and on the land determine the concentrations of nitrous oxide? How do variations in atmospheric nitrous oxide affect ozone concentrations in the stratosphere and troposphere?

(b) Energy Balance. Assessment of regional variations in the factors that determine the land energy

balance is critical to evaluation of the interactions between land conditions, climate, hydrology, and global productivity. Would an increase in surface albedo, for example, as a result of vegetation removal in the Amazon region, alter regional rainfall patterns due to positive feedback effects in the energy budget? In areas where rainfall is suppressed by this change, would further reductions in vegetation cover occur through reduced availability of the moisture needed for survival and growth of vegetation?

The factors that control the energy balance of the land include albedo, emissivity, thermal inertia, moisture availability, and surface roughness. These factors interact with atmospheric conditions to determine energy flux and balance. What are the relative roles and importance of these factors, particularly as a function of the differential characteristics of various global biomes?

(c) Hydrological Cycle. Our quantitative knowledge of the global water cycle is surprisingly poor. The volumes of water in ice and snow, underground water, and surface water are known to only ±50 percent. Even more significant, evaporation minus precipitation over land and ocean (or equivalently the net flow of water from land to oceans in rivers and the net advection of moisture from the marine to terrestrial atmosphere) is not known to within a factor of 2. Any attempt to understand and predict the delivery of water to the land-based biosphere is clearly hampered by such ignorance.

The fact that the global inventory of surface freshwater can be drained by evaporation and transpiration in 5 years or by rivers in 10 years points to the relevance of measurements of the global biospheric water supply on the 5- to 100-year time scale. In particular, what are the spatial and temporal distributions of rainfall and evapotranspiration over the landmass, and how do these distributions respond to changes in regional land use and to global climatic change? What is the budget of rainfall over land and ocean, and how is it affected by oceanic circulation? What is the magnitude of the net flow of water to the oceans via rivers, and how does this vary?

2. What Are the Effects of Climatic Changes on the Biosphere? How are the (a) quantity, (b) composition, and (c) distribution of living and nonliving components of the biosphere affected by climatic changes, including changes in seasonal averages and in magnitude of interannual variations of temperature, precipitation, cloudiness, and tropospheric ozone, and, for ocean biota, changes in ocean circulation and nutrient cycling?

(a) Quantity. Changes in the length of the growing season, brought about by shifts in the regimes of temperature or precipitation, will affect the balance between respiration and primary production, therefore changing the mass of the land biosphere and the atmospheric CO_2 content. The amplitude and phase of such climatically induced changes in components of the biosphere are unknown but could be studied in controlled greenhouse and field experiments by using models and by paleontological examinations of the interactions of biota with climate.

(b) Composition. While a considerable amount is known about climatically caused change in ecosystem composition from comparative studies of biological systems under different climatic regimes, many possibilities remain to be explored. For example, atmospheric warming may result in different cycles of mixing in the upper ocean and probably, therefore, its biological productivity. Greater knowledge of this possible effect depends on further development of coupled ocean-atmosphere simulation models, including effects on nutrient fluxes, and on studies of ocean-bottom cores laid down under different climatic conditions. Changing climatic regimes influence the composition of agronomic systems suitable for any geographic region.

(c) Distribution. The impact of climatic change on the various types of ecosystems will also affect their geographic distributions and thus metabolic response and carbon fluxes of elements. For example, changes in the distribution of organic matter in the biosphere, especially in land vegetation and soils, will affect the ease with which carbon can be oxidized, potentially raising concentrations of atmospheric carbon dioxide and resulting in further climatic feedback.

3. What Are the Causes and Effects of Changes in the Earth's Biogeochemical Cycles? The biogeochemical element cycles support biological productivity on land but, at the same time, are maintained in large part by plants and other organisms. The assimilation of carbon from the atmosphere by phototsynthesis, incorporation by consumer organisms, and release back to the atmosphere by decomposition is the fundamental pathway for material cycling through terrestrial ecosystems. The global element cycles are inescapably coupled with the Earth's energy balance and hydrologic cycle. Assimilation by photosynthesis is driven by solar energy, and water is a primary constituent of this biological process.

Broadly speaking, the questions are: What are the sources and sinks of C, N, P, S, O, and H and their compounds in the ocean, atmosphere, and biosphere? What are the transport mechanisms for these substances between geospheres, the chemical interactions among them, the residence times of different compounds in different geospheres, and their physical states? How do biological processes, primarily microbiological processes, affect the cycles of these substances? And how do they respond to climate?

(a) Carbon. Uncertainties in our understanding of the carbon cycle lead to serious difficulties in predicting future concentrations of atmospheric CO_2. There are a number of questions that must be addressed. At what rate is the carbon content of major terrestrial ecosystems changing? What factors control the biological uptake and release of carbon? What are the key processes that control the exchange of carbon between the atmosphere and ocean? What is the response of the carbon cycle to human perturbations?

(b) Nitrogen. What is the magnitude of the nitrogen fixation rate in major ecosystems? How much of this fixation is influenced by human activity, and how is the rate of fixation changing? Are anthropogenic disturbances of the nitrogen cycle causing changes in the fertility and productivity of major terrestrial ecosystems? Are stores of nitrogen in major soil systems increasing or decreasing? What effect does anthropogenic N have on rivers and coastal ecosystems? How has the atmosphere concentration of NO_x and N_2O been enhanced by emissions from combustion and agricultural soils, and what effects may be expected on other important species, such as ozone?

(c) Phosphorus. What is the magnitude of the riverborne flux of P to the ocean? How is the biological availability of this P controlled? Is productivity in the surface ocean limited by P? Would biological fixation of N increase substantially in coastal areas in response to increases in the flux of P to the ocean from rivers?

(d) Sulfur. What are the magnitudes of the biological and other fluxes of sulfur through the geospheres? What processes control these fluxes, and how have they been perturbed by human activity? What is the pattern of dispersion and chemical fate of industrially released SO_2, and how does acidification of the environment affect the biota?

DATA, METHODS, AND TECHNOLOGIES

In attempting to answer these questions, we must be concerned not only with measurements of present conditions but also with proxy or indirect measurements for past times when different conditions prevailed.

Here, as in many other problems of the dynamic Earth, the past is an important key to the present and future. Studies of ^{18}O and ^{14}C in varved lake sediments laid down 5,000-50,000 years ago should directly reflect atmospheric conditions at that time. This is in contrast to marine sediments, where the ^{18}O record is confused by salinity variations and the ^{14}C record reflects oceanic ^{14}C and not the atmospheric ^{14}C-^{12}C ratio. More generally, how can observed differences in the ratios of ^{12}C, ^{13}C, and ^{14}C be interpreted to estimate past changes in atmospheric CO_2?

Changes in the land have occurred rapidly during the past several decades and undoubtedly will occur rapidly in future decades. Many of these changes may be irreversible, and it is therefore urgent to develop suitable measurement programs within the next few years.

Measurements of the quantities of organic carbon in different land biomes and in the underlying soils should be made on a worldwide basis, as should changes in these quantities resulting from climatic variations and anthropogenic processes.

Many data already exist on recent changes in the land biota, particularly time series of satellite observations, and these should be preserved and made easily accessible to interested scientific workers. There is a need to continue the operation of these devices, especially of the AVHRR, Landsat, and Coastal Zone Color Scanner type of satellite sensors. These must continue to be used in combination with ground-based sampling (for calibration) and helicopter and aircraft sensors. Application of new remote-sensor developments is needed, especially with improved spectral-band selection for the determination of land biomass and biological productivity and the use of radar. The latter will be useful for areas with persistent cloud coverage, for determinations of soil moisture, and in differentiating types of land biomass.

The deployment of new satellite sensors to study physical and biological processes in the ocean is essential in order to develop insight into the spatial and temporal cycles of ocean biological productivity and carbon transport to deep waters. Time series of river

transport of dissolved and suspended substances through estuaries to the open sea will give important data, now largely missing, concerning the transfer of nitrogen, phosphorous, and other biologically important substances from the land to the ocean.

Analytic and simulation models of biospheric processes should be constructed and refined to guide measurement programs and to evaluate the data obtained.

Examples of biospheric research where international cooperation is essential include studies of suitable lake sediments and river transport and organic carbon measurements of different biomes and soils. Every effort should be made to encourage and support scientists in developing countries who are interested in measurements of this kind.

Appendix E

IGBP RELATED PROGRAMS AND PLANS

A. Solar-Terrestrial
   1. Solar Maximum Year
   2. International Magnetospheric Study
   3. Upper Atmosphere Research Satellite
   4. Origins of Plasmas in the Earth's Neighborhood
   5. Middle Atmosphere Program
   6. Nationally Coordinated Solar-Terrestrial Program
   7. Study of Traveling Interplanetary Phenomena

B. Oceans and Atmosphere (Including Hydrology)
   1. World Climate Research Program
   2. World Climate Data Program
   3. Global Atmospheric Research Program
   4. World Weather Watch
   5. World Ocean Circulation Experiment
   6. Tropical Oceans and Global Atmosphere Program
   7. Equatorial Pacific Ocean Climate Studies
   8. Integrated Global Ocean Services System
   9. Global Tropospheric Chemistry Program
   10. International Hydrological Program

C. Lithosphere
   1. International Geological Correlation Program
   2. International Lithosphere Program

D. Biosphere
   1. Man and the Biosphere
   2. Analyzing Biospheric Change
   3. A Decade of the Tropics
   4. Global Environmental Monitoring System

E. Other Broad Multidisciplinary Programs
   1. The CO_2 Fingerprint
   2. Global Habitability Program (NASA)
      (a) Global Biology Research Program
      (b) Land-Related Global Habitability Sciences Research Program
      (c) A Biogeochemical Perspective on Global Habitability
   3. The Biogeochemical Cycles and Their Interactions (SCOPE)
   4. Climatic, Biotic Human Interactions in the Humid Tropics
   5. Fundamental Research on Estuaries

TABLE E.1 IGBP-Related Programs and Plans

Program	Observing Program: Dedicated	Observing Program: Other	Status of Observational Phase	Current Arena	Disciplines	International Focus	National Focus
A. SOLAR-TERRESTRIAL							
1. Solar Maximum Year (SMY)	x		Past	International	Solar-terrestrial physics	SCOSTEP	NASA, NSF
2. International Magnetospheric Study (IMS)	x		Past	International	Solar-terrestrial physics	SCOSTEP	NAS, NASA, NOAA, NSF, USGS
3. Origins of Plasmas in the Earth's Neighborhood (OPEN)	x		Proposed	National	Solar-terrestrial physics		NASA
4. Middle Atmosphere Program (MAP)	x		Ongoing (continuation proposed)	International	Solar-terrestrial physics, meteorology	SCOSTEP	NASA, NSF, NOAA, DOD
5. Nationally Coordinated Solar-Terrestrial Program	x		Proposed (not implemented)	National	Solar-terrestrial physics	--	Committee on Atmosphere and Oceans (terminated)
6. Study of Travelling Interplanetary Phenomena	x		Ongoing	International	Solar-terrestrial physics	SCOSTEP	NASA, NSF, DOD, NOAA

B. OCEANS AND ATMOSPHERE (INCLUDING HYDROLOGY)							
1. World Climate Research Program (WCRP)	x		Ongoing	International	Meteorology, oceanograpny	WMO/ICSU	NAS, NOAA
2. World Climate Data Program		x	Ongoing	International	Meteorology, oceanography	WMO/ICSU	NOAA
3. Global Atmospheric Research Program (GARP)	x		Past	International	Meteorology, oceanography	WMO/ICSU	NOAA, NSF NASA
4. World Weather Watch (WWW)	x		Ongoing	International	Meteorology	WMO	NOAA
5. World Ocean Circulation Experiment (WOCE)	x		Proposed	International	Oceanography, meteorology	WCRP/CCCO	NASA, NSF
6. Tropical Oceans and Global Atmosphere (TOGA)	x		Proposed	International	Meteorology, oceanography	WCRP/CCCO	NASA, NSF, NOAA
7. Equatorial Pacific Ocean Climate Studies (EPOCS)	x		Ongoing	National	Meteorology, oceanography	--	NOAA, NSF
8. Integrated Global Ocean Services System (IGOSS)	x		Ongoing	International	Oceanography	IOC, WMO	NOAA

TABLE E.1 Continued

Program	Observing Program: Dedicated	Observing Program: Other	Status of Observational Phase	Current Arena	Disciplines	International Focus	National Focus
9. Global Tropospheric Chemistry Program	x		Ongoing	National	Atmospheric chemistry	--	NAS, NSF
10. International Hydrological Program (IHP)		x	Ongoing	International	Hydrology, geology	UNESCO	USGS, DOD
C. LITHOSPHERE							
1. International Geological Correlation Program (IGCP)	x		Ongoing	International	Geology, solid-earth physics, geochemistry	IUGS/UNESCO	USGS, NSF
2. International Lithosphere Program (ILP)	x		Ongoing	International	Solid-earth physics	IUCL	NSF, USGS, NASA, NOAA, DOE, DOD
D. BIOSPHERE							
1. Man and the Biosphere (MAB)		x	Ongoing	International	Ecology	UNESCO	Department of the Interior
2. Analyzing Biospheric Change (ABC)		x	Ongoing	International	Ecology, biology, meteorology, oceanography, social science	IFIAS	NCAR
3. A Decade of the Tropics		x	Ongoing	International	Biology	IUBS	--

4. Global Environmental Monitoring System (GEMS)	x	Ongoing	International	Meteorology, environmental sciences, ecology	UNEP	Department of State
E. OTHER BROAD MULTIDISCIPLINARY PROGRAMS						
1. The CO_2 Fingerprint	x	Proposed	National	Geophysics	--	NAS
2. Global Habitability Program (NASA)						
a. Global Biology Research Program	x	Proposed	National	Biology, meteorology, chemistry, oceanography, ecology	--	NASA
b. Land-Related Global Habitability Sciences Research Program	x	Proposed	National	Biology, meteorology, chemistry, ecology	--	NASA
c. A Biogeochemical Perspective on Global Habitability (McElroy document)	x	Proposed	National	Biology, meteorology, chemistry, oceanography	--	NASA

TABLE E.1 Continued

Program	Observing Program: Dedicated	Observing Program: Other	Status of Observational Phase	Current Arena	Disciplines	International Focus	National Focus
3. The Biogeochemical Cycles and Their Interactions (SCOPE report)		x	Ongoing	International	Biology, meteorology, oceanography, chemistry	SCOPE	--
4. Climatic, Biotic, Human Interactions in the Humid Tropics	x		Proposed	International	Meteorology, biology, ecology, pedology, oceanography	United Nations University	--
5. Fundamental Research on Estuaries	x		Proposed	National	Meteorology, geology, biology, oceanography, chemistry	--	NAS

ABSTRACTS OF PROGRAMS AND PLANS

A. SOLAR-TERRESTRIAL

1. Solar Maximum Year (SMY). SMY was organized by the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP) and ran from August 1979 to March 1981. About 400 scientists at 60 observatories from 27 countries participated in the program, using high-resolution magnetograms, radio records, very-high-resolution (1") microwave radio maps, and space observations during a period of an active Sun. SMY is now moving into a postmonitoring data-analysis phase.

2. International Magnetospheric Study (IMS). IMS was an international, coordinated effort to study the magnetosphere--the region of near-Earth space that directly affects our environment. IMS produced a data base for exploratory research into links between climatic and weather variations and geomagnetic phenomena. About 50 countries participated in spacecraft, ground-based, balloon, aircraft, and rocket programs. The simultaneous spacecraft and coordinated observations provide a unique opportunity to separate time and space variations in the magnetosphere.

3. Upper Atmosphere Research Satellite (UARS). A multisatellite NASA program to investigate the radiative energy balance, chemistry, and dynamics of the stratosphere, mesosphere, and lower thermosphere. This program is the major component of the U.S. national plan to study the basic state of the middle atmosphere, its natural variability, and response to various solar-terrestrial perturbations.

4. Origins of Plasmas in the Earth's Neighborhood (OPEN). The OPEN program is in the planning stage under the auspices of NASA and is currently functional at the national level. The goal of OPEN is to obtain the first quantitative assessment of the global flow of energy through the Earth's space environment above the upper atmosphere. This will be accomplished with a network of four spacecraft orbiting strategically in four key locations around the Earth. The spacecraft will provide simultaneous measurements of the charged-particle radiation and magnetic and electric forces that transfer, store, and dissipate energy through the Earth's dynamic space environment.

5. Middle Atmosphere Program (MAP). MAP is an ongoing initiative of SCOSTEP. The major objectives of MAP are to obtain the scientific knowledge necessary to answer these important questions: (1) What are the possibilities for damage to the Earth's middle atmosphere as a result of mankind's activities (e.g., the permanent reduction of the ozone concentration in the stratosphere); (2) what role does the middle atmosphere play in determining climate and climatic changes; and (3) what are the processes by which the Sun, acting through the middle atmosphere, may be able to affect weather?

6. Nationally Coordinated Solar-Terrestrial Program. The former Committee on Atmosphere and Oceans Policy Review Group established a Solar-Terrestrial Task Group to define the needs, opportunities, and conduct of a nationally coordinated program to study our solar-terrestrial environment. The Task Group noted that such a program is needed and will benefit the overall U.S. solar-terrestrial effort in both basic research and technical applications, the latter related directly to national security and societal systems. Furthermore, coordination should be based on existing and planned federal agency programs, and the program should be operational by 1980 and extend to 1991, one solar cycle. The program has yet to be implemented.

7. Study of Travelling Interplanetary Phenomena (STIP). STIP was organized by the Scientific Committee on Solar Terrestrial Physics (SCOSTEP) in 1973. It consists of 400 scientists from more than 25 countries representing 100 national institutions performing in situ experiments, remote-sensing and theoretical analyses of solar, interplanetary, cosmic-ray, and astrophysical phenomena to define the state of the interplanetary medium between the Sun and any object (e.g., Earth, Jupiter, comet) that receives any impulse from these traveling disturbances. Traveling disturbances are defined in their own right but also in the context of the previously undisturbed Sun and interplanetary medium. Observations are brought together to form synoptic descriptions of retrospective intervals (e.g., 2 months).

B. OCEANS AND ATMOSPHERE (INCLUDING HYDROLOGY)

1. World Climate Research Program (WCRP). The major objectives of the WCRP, which is conducted jointly by the

World Meteorological Organization (WMO) and the International Council of Scientific Unions (ICSU), are to determine (1) to what extent climate can be predicted and (2) the extent of man's influence on climate. The overall work to be carried out in the WCRP has been described in a Preliminary Plan, prepared in January 1981 under the guidance of the WMO/ICSU Joint Scientific Committee. The Preliminary Plan recommended that the strategy to meet the objectives of the WCRP should include (1) the study of climatologically significant processes, (2) the development of physical-mathematical models of the climate system, and (3) the statistical analysis of observed climate variables. The Joint Scientific Committee singled out for particular attention (1) the controlling effect of cloudiness on the radiation energy budget of the climate system and (2) the effect of the physics and dynamics of the oceans on the global cycles of heat, water, and chemicals (especially carbon) in the climate system.

2. World Climate Data Program. The World Climate Data Program is a component of the World Climate Program organized under the WMO. A plan for the World Climate Data Program emphasizes aid to individual countries to upgrade their capabilities in climate data management to rescue, digitize, quality control, store, retrieve, and use climate data. The elements constituting climate data from the atmosphere-ocean-cryosphere-solid Earth climate system are upper-air, surface climate, ocean surface and subsurface, cryosphere, radiation budget, atmospheric composition, hydrosphere, land and vegetation, proxy, and solar data.

3. Global Atmospheric Research Program (GARP). GARP was organized by the WMO-ICSU Joint Organizing Committee. GARP is a program for studying those physical processes in the troposphere and stratosphere that are essential for an understanding of (1) the transient behavior of the atmosphere as manifested in the large-scale fluctuations that control changes of the weather; this would lead to increasing the accuracy of forecasting over periods from one day to several weeks; (2) the factors that determine the statistical properties of the general circulation of the atmosphere, which would lead to better understanding of the physical basis of climate. The program consists of two distinct parts, which are, however, closely interrelated: (1) the design

and testing by computation methods of a series of theoretical models of relevant aspects of the atmosphere's behavior to permit an increasingly precise description of the significant physical processes and their interactions; (2) observational and experimental studies of the atmosphere to provide the data required for the design of such theoretical models and the testing of their validity.

4. World Weather Watch (WWW). The WWW is a program of WMO and has the primary purpose to make available to each Member State the basic meteorological and other relevant environmental information it requires for efficient and effective meteorological services as regards both the application of meteorology and research. The World Weather Plan includes three essential operational elements, namely, the Global Observing System, the Data Processing System, and the Global Telecommunication System.

5. World Ocean Circulation Experiment (WOCE). The objective of WOCE is to describe and understand quantitatively the general circulation of the ocean, in order to assess within the World Climate Research Program the sensitivity of the climate system to changes in external forcing, whether natural or anthropogenic, on time scales of decades to centuries. The observational core of the experiment emphasizes large-scale processes and internationally coordinated field programs; these should be supplemented by a number of more local programs oriented to the mechanisms of particular processes. Attaining the WOCE objective will require evolution of a hierarchy of models ranging from idealized conceptual models through statistical data assimilation models. WOCE also has an observational program to provide information that will constrain such models and increase their credibility for experiments on climate system sensitivity. WOCE should be a peak activity during the late 1980s when the required oceanographic statellites are operational.

6. Tropical Oceans and Global Atmosphere (TOGA) Program. TOGA is one element in the World Climate Research Program. The motivation for TOGA arises out of the convincing demonstration that sea-surface temperatures (SST) in the tropical oceans are correlated with the global atmospheric circulation on time scales of a year or more. The overall objective of TOGA is to understand the relation between heat-flux anomalies (SST as well as

wind and humidity fields) in the tropical oceans and the associated changes in the global atmospheric circulation. These processes occur over periods of decades, so measurements should span a decade. However, shorter programs, presumably at a higher level of intensity than the long-term ones, can make major contributions.

7. Equatorial Pacific Ocean Climate Studies (EPOCS). EPOCS is a program that was established in 1979 by the National Oceanic and Atmospheric Administration (NOAA) under the charter of the Climate Program Act. The primary task of EPOCS is to investigate large-scale tropical Pacific ocean-atmosphere interactions and their impact on seasonal-interannual climate fluctuations. The general objectives of EPOCS are (1) to develop an improved historical record of sea-surface temperatures (SST) and surface wind anomaly fields, (2) to describe and understand the local and remote effects of known SST anomalies on the atmospheric circulation, (3) to describe and understand the evolution of SST anomalies as part of the response of the ocean to given atmospheric forcing, and (4) to study the feedback systems involved in the maintenance and evolution of anomalous oceanic and atmospheric conditions.

8. Integrated Global Ocean Services System (IGOSS). IGOSS is cosponsored by the Intergovernmental Oceanographic Commission of UNESCO and the World Meteorological Organization. IGOSS is a worldwide ocean services program with the purpose to promote, develop, and coordinate the international organization necessary for the global acquisition and exchange of ocean data and the dissemination of oceanographic products and services to governmental, commercial, academic, and private interests. Major real-time ocean analysis products currently produced by Member States for various ocean areas include sea-surface and subsurface temperatures, mixed-layer depths, and ocean frontal positions. Additional summaries are available in delayed-mode dissemination including currents, salinity, distributions of pollutants, and weekly and monthly temperature means.

9. Global Tropospheric Chemistry Program. The Global Tropospheric Chemistry Program is being conducted under the aegis of the National Academy of Sciences with some support from NSF. The objectives of the program are (1) to evaluate biological and abiological sources of

chemical substances in the troposphere, (2) to determine the global distribution of tropospheric trace species, (3) to test photochemical theory through field and laboratory investigations of photochemically driven transformation processes, and (4) to investigate wet and dry removal processes for trace gases and particles. To meet these objectives requires development of a wide range of models including models of individual processes important for tropospheric chemistry as well as comprehensive global models addressing all relevant chemical and meteorological processes. Sensitive instrumentation will also be required for the measurement of chemical species in the remote troposphere. Although the Global Tropospheric Chemistry Program is proposed as an international initiative, it is, in its current status, operational at the national level.

10. International Hydrological Program (IHP). UNESCO initiates and coordinates research that will contribute to a better knowledge of the hydrological system and serve as a basis for the exploitation and better management of water resources. U.S. participation in IHP is coordinated by the U.S. National Committee for the IHP sponsored by the U.S. Geological Survey. IHP cooperates with WMO, UNEP, and IAHS/IUGG.

C. LITHOSPHERE

1. International Geological Correlation Program (IGCP). IGCP is supported jointly by the International Union of Geological Sciences (IUGS) and UNESCO. The early focus of IGCP was to better understand stratigraphic correlations between rock sequences as the sequences vary spatially. IGCP has recently broadened in scope to promote worldwide organization and distribution of knowledge about geological resources and environment. At the end of 1981 there were 78 IGCP national committees active with 49 ongoing projects.

2. International Lithosphere Program (ILP). ILP is a new international interdisciplinary research program in the solid-Earth sciences that has been established by ICSU through the Inter-Union Commission on the Lithosphere (ICL). The main objective of the program is the elucidation of the nature, dynamics, origin, and evolution of the lithosphere, with special attention to the continents and their margins. Investigations of the lithosphere

beneath the oceans and of parts of the Earth below the lithosphere are also included to meet the scientific objectives of the program. The problems to be investigated are interdisciplinary and global in scope, and they require international cooperation involving the coordinated efforts of geophysicists, geodesists, geologists, and geochemists. Moreover, the full scientific potential of the program can only be attained with the active participation of scientists concerned with geoscience applications and scientists from developing countries.

D. BIOSPHERE

1. Man and the Biosphere (MAB). MAB is a special program of UNESCO. It initiates and coordinates a series of multinational research projects on the effects of human activities on various ecosystems, including land-use management, energy utilization, and resource conservation. U.S. liaison and participation in MAB is conducted by the U.S. National Committee for MAB, sponsored by the Departments of Energy and Agriculture. MAB cooperates with a number of organizations including UNEP, the Food and Agriculture Organization (FAO), WHO, WMO, ICSU, and the International Union for Conservation of Nature and Natural Resources (IUCN).

2. Analyzing Biospheric Change (ABC). ABC is a program of the International Federation of Institutes for Advanced Study (IFIAS) with emphasis on the documentation and analysis of the dynamics of the man-environment system. Special attention is given to four problem areas: (1) analysis of the dynamics of the man-society-environment relations in urban systems, (2) the dynamics of certain of the more vulnerable agricultural systems, (3) deforestation and its influence on soil erosion and the viability of local communities, and (4) analysis of the rational utilization of the various resources present in the coastal zone. More generalized studies are undertaken to develop the conceptual and methodological framework for these problem areas but which draw on wider experience of interaction between man and his environment. The ABC program receives some financial support from IFIAS, but a majority of support comes from outside funding agencies and research institutes.

3. A Decade of the Tropics. A Decade of the Tropics is a program of the International Union of Biological Sciences (IUBS) that focuses on improving basic scientific understanding of tropical biological systems. The objective of the Decade of the Tropics is to facilitate opportunities for travel in connection with research, to increase the communication among scientists through meetings, publications, and diffusion of the results of their work. The guiding principle will be collaboration, with special emphasis on the scientific community resident in the tropics.

4. Global Environmental Monitoring System. Earthwatch was proposed at the United Nations Conference on the Human Environment in Stockholm in 1972 and is now part of the United Nations Environment Programme (UNEP). The Global Environmental Monitoring System is one of four components of Earthwatch; the others are evaluation, research, and the exchange of information. In 1972, UNEP established a Program Activity Center for GEMS, which coordinates international monitoring activities conducted throughout the world, mainly under the aegis of specialized agencies of the United Nations and consisting of networks of nationally operated monitoring systems. As with UNEP as a whole, the GEMS Center is not operational (i.e., it does not itself operate monitoring stations). GEMS monitoring activities fall into five closely linked categories: health-related monitoring, climate-related monitoring, renewable-resources monitoring, ocean monitoring, and international-disaster monitoring.

E. OTHER BROAD MULTIDISCIPLINARY PROGRAMS

1. The CO_2 Fingerprint. The CO_2 Fingerprint: A Strategy for Detection is a report emerging from a study being coordinated by the National Academy of Sciences. The study addresses the problem of detecting the existence and magnitude of a hypothesized CO_2 effect on climate against the background of climatic variability, which may be in part random and in part explainable in terms of fluctuations in external factors. The study has tentatively concluded that an approach that should be pursued is development of a composite index of parameters expected to respond more strongly to changes in CO_2 (and other greenhouse gases) than to other factors that may influence climate. Such an index would permit tracing the unique "fingerprint" of the greenhouse gases on climatic

variation. The study proposes that such an approach should be implemented in a multidisciplinary, international program that includes an extensive global monitoring network as well as development of a composite index to detect the CO_2 fingerprint.

2. Global Habitability Program (NASA)

(a) Global Biology Research Program. Global biology is a new initiative within the Life Sciences Division of the Office of Space Science and Applications of NASA. A series of workshops were held in 1979, 1980, and 1981 to develop a comprehensive program in global biology. Out of the workshops came a document representing a global biology research program plan. It includes a scientific rationale and prescribes research activities for developing an understanding of biospheric dynamics revealed by the interaction between the biota and the environment. Issues to be confronted in the first 10 years of the program are existing data identification and development of a data network, biomass size and distribution, ecosystem areal extent and rates of change, atmospheric trace-gas flux measurements and factors affecting magnitude, and development of biogeochemical cycle models and elemental linkages.

(b) Land-Related Global Habitability Sciences Research Program. The Earth and Planetary Exploration Division in the Office of Space Sciences and Applications of NASA produced this report to serve as an overall planning document for a Land-Related Global Habitability Sciences Research Program. The overall goal of this program is to achieve improved understanding, an accessible research information base, and predictive simulation modeling of physical, chemical, or biological changes on the land caused by natural events or human choices that over the long term (5-50 years) significantly affect global productivity or life-support cycles as measures of primary human needs for food, water, and suitable climate. The plan for this program builds on the June 1982 Woods Hole Workshop that produced the report Global Change: Impacts on Habitability.

(c) A Biogeochemical Perspective on Global Habitability. This study builds on the principles described in Global Change: Impacts on Habitability (1982). That document stressed the importance of changes

in the geobiochemical cycles of water, plant nutrients, and toxins. This study proposes development of a program to examine these cycles through detailed studies of the chemistry, physics, and biology of the atmosphere, the oceans, and the land surface, considered both individually and as a single interacting system. Because the problems being addressed involve a 5-50-year time scale, the time for data-set development cannot be much shorter. The program is proposed to be carried out over decades, although it may be phased in such a way as to complete some studies before others.

3. The Biogeochemical Cycles and Their Interactions. This is a report that was produced to provide an overview of contributions and discussions at the Scientific Committee on Problems of the Environment (SCOPE) Workshop on the Interaction of Biogeochemical Cycles in Ursundsbro, Sweden, in May 1981. This report focuses on man's ability, through his activities on Earth, to induce fluxes of carbon, nitrogen, phosphorus, and sulfur that are comparable in magnitude with those associated with the natural cycles of these elements.

4. Climatic, Biotic, and Human Interactions in the Humid Tropics. This is a program that is being developed by the United Nations University to investigate the need for monitoring biotic and climatic interactions in the humid tropics and to improve understanding of human impact on the climatic-biotic system. The objective of such a program would be to seek answers to such questions as: (1) What are the various interactions within ecosystems at the microlevel and the principles that govern them, (2) what are the interactions between the climatic and biotic systems and the principles that govern them, (3) what are the results of various types of human activities on the natural climatic-biotic system and the reactions of the system to such impact? A systems-analytic approach can be taken to conceptualize and model these interactions. The interdisciplinary nature of the program requires participation by leading experts on climate, elemental recycling, hydrology, ecology, modeling, systems analysis, and other fields.

5. Fundamental Research on Estuaries. In 1977 the Geophysics Research Board (GRB) of the National Research Council published a report on Estuaries, Geophysics, and the Environment. As a follow-up effort to further define

an estuarine research focus, a Panel of the GRB produced the report Fundamental Research on Estuaries: The Importance of an Interdisciplinary Approach (1983). The report identified three major components of the entire estuarine system needing integration: (1) environmental effects on estuarine biota, (2) circulation and mixing in estuarine and coastal waters, and (3) suspended and dissolved matter in estuaries. Because of the complexity of the components, the Panel recommended that (1) the primary focus of future research in estuaries should be on interdisciplinary relationships and (2) such interdisciplinary research in both university and governmental laboratories should receive increased support to provide the basic framework for informed management of estuarine systems.

Appendix F

PARTICIPANTS, INTERNATIONAL GEOSPHERE-BIOSPHERE PROGRAM WORKSHOP
Woods Hole, Massachusetts, July 25-29, 1983

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