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# Global Change in the Geosphere-Biosphere

Initial Priorities for an IGBP



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U.S. Committee for an  
International Geosphere-Biosphere Program  
Commission on Physical Sciences, Mathematics,  
and Resources  
National Research Council

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## FOREWORD

Cooperation in observation and research has long been the hallmark of the earth sciences. In the seventeenth century, Hadley laboriously developed an understanding of the global atmospheric circulation and the trade winds from carefully collected ships' logs. By the nineteenth century, formally organized international scientific activities began to take shape, such as the First Polar Year of 1882-1883. In the same period, international networks of weather observations emerged that have continued through the present. In our own century, the International Geophysical Year (IGY) of 1957-1958 not only created an unprecedented treasure trove of coordinated data but also spawned a host of successor programs, some of which are still in progress.

For the most part, these programs focused on one or another component of our complex planet and primarily involved the scientific disciplines specialized to address that component. For example, the Global Atmospheric Research Program (GARP) addressed the large-scale circulation of the atmosphere; through its observational programs and coordinated research efforts, meteorologists and oceanographers greatly advanced our understanding of the processes determining weather and climate variability. The power of space-based observations of solar radiation and its role in global stratospheric photochemistry has further exposed the vast complexity of atmospheric processes at high altitude.

The very success of these endeavors within the various disciplines of the earth sciences, however, has made us aware of their limitations. As we have learned more about the workings of the Earth's atmosphere, oceans, biota, space environment, solar variability, and indeed the solid Earth itself, we have become increasingly aware of the *interactions* among these components. Indeed, it has become increasingly evident that the most scientifically challenging and socially important problems facing the environmental sciences lie at the *interfaces* between these components, and thus between the established disciplines of the sciences of the geosphere and biosphere.

The modern view of the Earth as a scene of continual change, and of mankind as an increasingly potent agent for change, heightens the



importance of these interactions. The richly detailed chronology of massive global changes in the Quaternary associated with the advance and retreat of the great ice sheets can be understood only in a framework that encompasses ocean chemistry and biology, lithospheric dynamics, solar and orbital variations, and the terrestrial biota. Understanding future environmental changes that may be induced by mankind's transformation of the Earth's surface and the atmosphere's composition will require an even greater breadth of investigation that includes the social sciences.

Such considerations, inspired by the twenty-fifth anniversary of the IGY, have generated a number of initiatives aimed at fostering international, interdisciplinary, and global-scale studies. A unifying theme was cogently stated by George Garland in an International Council of Scientific Unions (ICSU) lecture commemorating the twenty-fifth anniversary of the IGY. He remarked that the "mysteries" that remain in our understanding of the planet involve the interaction between physical and biological processes, including those processes dominated by human actions. A group of scientists advising the National Aeronautics and Space Administration (NASA) under the leadership of Richard Goody called for a program to address the continued "habitability" of the planet. Within the National Research Council (NRC), I encouraged discussions of future international interdisciplinary programs by the several units of the NRC concerned with the natural sciences. The latter round of consultations led to the organization of a major workshop held at Woods Hole, Massachusetts, in the summer of 1983. This workshop addressed a broad range of research problems in the atmosphere, oceans, lithosphere, biosphere, and solar-terrestrial relationships. The report of the workshop emphasized the importance of the topic of global change and urged the further development of programmatic concepts on the national and international levels.

At about the same time, the NASA Advisory Council appointed an Earth System Sciences Committee chaired by Francis P. Bretherton to formulate an implementation strategy. This Committee is focusing its attention on the problems of global changes that will occur in the next decade to century and seeking to integrate the earth sciences in a broad, global perspective.

The broadly based recommendations of the NRC group were carried to ICSU and were enthusiastically received. Under the leadership of Juan Roederer and Thomas F. Malone, a wide-ranging symposium was organized in conjunction with the 1984 ICSU General Assembly in Ottawa. Motivated by this sweeping panorama of vital and challenging problems, the General Assembly appointed a steering group and set in motion a two-year study of the requirements for international programs to address global change, a study that is in progress as I write.

Another outcome of the NRC workshop was the establishment of a U.S. Committee for an International Geosphere-Biosphere Program, the

name we had provisionally attached to a yet-undefined effort. This distinguished group, led by John A. Eddy, sought to focus on a manageable number of important and timely scientific issues and research problems within the scope of this evolving international effort. The Committee's report emphasizes the interactions that influence global-scale changes on time scales of decades to centuries, and particularly the interactive physical, chemical, and biological processes that regulate the Earth's unique environment for life. Importantly, the programs they propose address the insights we can hope to gain into these interactions by reconstruction of the Earth's past natural experiments in global change, observation of contemporary conditions from earthbound and spaceborne platforms, and coordinated research to achieve understanding and permit prediction.

As the International Geosphere-Biosphere Program evolves, other scientists will be motivated by the intellectual challenge of understanding even the most remotely coupled elements of the terrestrial system from the core of the sun to the center of the earth. Such themes are emerging from scientists concerned with solar-terrestrial physics and solid earth sciences.

The Committee has deliberately focused on a set of problems never adequately addressed in a comprehensive interdisciplinary thrust: a set that seem particularly pressing and timely for attack. We hope that these recommendations will contribute to the great dialogue now developing among scientists of many nations and diverse agendas aimed at understanding the nature of global change and the processes that determine it. In this dialogue, these specific proposals almost certainly will be further developed, augmented, and reshaped. What we all wish to emerge is more than a collection of narrow disciplinary investigations. The problems of global change in the geosphere-biosphere, such as those identified in this report, call for a renaissance in the study of the Sun-Earth system as a dynamic, physical, chemical, living environment that is yielding more and more evidence of cross linkages between all its traditional disciplinary domains. That is the challenge of global change to the international community of science and the ultimate goal of these first initiatives.

Herbert Friedman, *Chairman*  
Commission on Physical Sciences,  
Mathematics, and Resources

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## PREFACE

The notion of uniting certain efforts of the earth and biological sciences in a common, international research program began to take form in the United States through actions of a number of groups and individuals over the past three years. In September 1984, the concept was formally presented and favorably received at the 20th General Assembly of the International Council of Scientific Unions held in Ottawa. The goal as originally conceived was to mount an effort to address an array of problems of global scale within disciplines of earth science, oceanography, atmospheric science, solar-terrestrial physics, and biology. The proposed theme, as enunciated in a preliminary U.S. National Research Council (NRC) Summer Study of 1983, was *global change* and the implications of environmental change for man and the future. A rallying point for a great number of scientists was the realization that most of the pressing environmental issues that now face us transcend the bounds of traditional scientific disciplines and that as global problems they require more than national efforts for their solution.

The NRC 1983 Summer Study\* laid out a long list of questions that might be addressed in a proposed International Geosphere-Biosphere Program (IGBP). The charge to the U.S. Committee for an IGBP, formed early in 1984, was to take the next and harder step: to give the program a clearer focus, by selecting a cohesive set of compelling problems that clearly require an international effort--questions for which we now have adequate technology and a sound scientific base, which truly need a new program for successful resolution, and which can be expected to attract the involvement of a multidisciplinary community of creative scientists.

Our Committee met for a week at the National Academy of Sciences Woods Hole Study Center in June 1984 and for shorter meetings on four other occasions during the year. As a group we represented a wide range of scientific disciplines and a diverse background of experiences and philosophy. Yet there was from the start a remarkable agreement

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\* *Toward an International Geosphere-Biosphere Program*, National Academy Press, Washington, D.C., 1983.

as to the need for a coherent international program, and a real enthusiasm for it.

In this report we outline the elements of a program that is focused sharply on fundamental problems that have urgent practical implications. These elements define a program that would attempt to understand the workings of the Earth and the living organisms on it as a coupled system --- a challenge in science that holds the promise of elucidating many of the global concerns of the present day. It would require the participation of many nations and draw upon the efforts of many fields of science. It would be made up of an array of planned, cooperative programs of observation, modeling, and process studies with organized opportunities for joint discussion and interpretation. It would lean on spaceborne observations for global perspective, but it is not a "space program," for the preponderance of needed science would deal with processes of change, and the vast majority of necessary measurements would need be made on the ground and on the oceans, from within the habitat of life. As an international program it would stand as a separate, focused endeavor that interacts with related, disciplinary programs to increase their effectiveness but without attempting to subsume them or to dictate their goals. And, it is a program that to us seems so clearly needed and compelling that it must be started now.

What we have drawn is not a set of blueprints but an architectural plan: a reasoned design for a needed program of world research, with suggestions of the sorts of research efforts that are central to its success. The more elaborate plans of these various endeavors need to be made internationally and with the counsel of a much larger number of specialists in all the fields involved.

We acknowledge contributions from Herbert Friedman and Thomas F. Malone, Advisors to the Committee, and the financial support of the Day Fund of the National Academy of Sciences and the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), the Department of Energy, the Department of Interior and the U.S. Navy. Joseph Berry, Thomas Donahue, Devrie Intriligator, and Juan Roederer gave their time as invited participants at Woods Hole, as did Louis Brown (National Science Foundation), Robert Mahler (NOAA), and Robert Murphy, Shelby Tilford, and Robert Watson (NASA). We also thank John Perry, Robert Chen, Peter Abel, William Easterling, Nancy Maynard, Judith Marshall, and Doris Bouadjemi for staff support.

John A. Eddy, *Chairman*  
U.S. Committee for an International  
Geosphere-Biosphere Program

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# 1 INTRODUCTION

There is a strong current felt by governments and policy makers throughout the world to come to grips with a series of growing concerns that deal with the global environment. To the layman these concerns are perceptible issues of air and water and a changing landscape, and a gnawing sense that the ever growing activities and numbers of man have already degraded the quality of life--if not the future habitability of the planet. To the scientist they are complex problems of atmospheric chemistry and ocean dynamics, of hydrology and biology that involve but also reach beyond the conventional, bounded fields of disciplinary study. Their solution, almost all would agree, rests in strengthening the base of knowledge in all the sciences that deal with the Earth. But it requires something more that is harder to obtain: a global view and a new effort to study the Earth and its living inhabitants as a tightly connected system of interacting parts--an endeavor in which scientific disciplines forsake their accustomed imperatives and serve as tools rather than ends in themselves. An effort so defined has no real precedent, for it would require not only the cooperation of nations but an intercourse and sharing between fields of study that are often seen as isolated and territorial. We think the need for action is so great as to warrant the mounting of a bold new program, and the issues so urgent and compelling that it must be started now. It is propitious that today we hold the means, in recent advances in science and technology, to mount such a program and to expect a measure to expect a measure of success.

We live on a unique planet with an ocean of liquid water and an atmosphere capable of sustaining and protecting life. Moreover the atmosphere, hydrosphere, and surface layers of the Earth are not the product of inorganic processes alone but the result of a synergism between living and nonliving parts, with the former often dominant. What must impress us is the delicacy of the balance that obtains. What must alarm us are the pervasive changes that we have wrought--in air and water and soils--in but the last instant of geologic time. Among these are the dramatic, year-to-year increases now documented in atmospheric CO<sub>2</sub> and methane and other greenhouse gases that through natural processes regulate the surface temperature of the Earth.



The bulk of the changes that affect the course of life and the environment of Earth are natural ones, induced by such inexorable forces as natural selection, the Sun-Earth distance, the shifting of winds and rivers, the turbulent dynamics of the atmosphere and ocean, the drifting of continental plates, the building of mountains, and the expansion and contraction of ice masses. But imposed on these is now another set of changes, more recent and immediate in consequence, that are the clear result of the hand of man. Human energy production and intensive farming and technology have altered the albedo of the Earth, the composition of the soil and waters, the chemistry of the air, the areas of forests, the balance of the global ecosystem, and the diversity of plant and animal species.

More than 10 percent of the land area of the Earth is now under cultivation. More than 30 percent is under active management for purposes of mankind. Chemical compounds for which there are no natural analogues are being produced and released into the air and water in ever growing proportions, and rates of natural chemical and hydrologic cycles have been altered with currently unpredictable consequences for climate and the local and global environment. Policy makers are faced with a baffling array of problems--apparent damage to large forest regions in Europe, deterioration of lakes in Scandinavia and eastern North America, climatic impacts of deforestation in the tropics, fluctuations in the extent of deserts in Asia, Africa, and North America, depletion and pollution of groundwaters, and growing levels of tropospheric oxidants, to mention but a few. There are increasing demands for action and for reliable information. In many cases uncertainties in our understanding of the complex interdependencies of the geosphere and biota hamper our ability to identify causes or effects or to anticipate the costs and benefits, economic and environmental, of possible responses.

In spite of the need and desire to know how Nature will respond to these perturbing human actions, we are obliged to admit that reliable predictions of neither the occurrence nor the consequences of such changes is currently possible. There are two reasons for this. The first is that we lack an adequate understanding of the way in which the global environmental system operates. We know there are strong interactions between such elements as solar radiation, atmospheric circulation, cloud cover, ocean currents, the Earth's biota, sea-ice cover, and atmospheric chemistry. Yet as a rule we know too little about the global dimensions and physics of these phenomena to offer more than a qualitative (and often speculative) description of their connections. A major challenge for an International Geosphere-Biosphere Program (IGBP), therefore, is to marshal the resources needed to advance our understanding of the way that individual elements operate. Only when this is achieved can the larger questions regarding feedbacks among many of the elements be properly understood and satisfactorily incorporated into useful, coupled

models of the coupled environment. The second reason that environmental forecasting is difficult is that the impacts of human actions are convolved in a natural pattern of environmental change. In effect, the environmental scientist is asked to read an anthropogenic "signal" imbedded in an incompletely defined background of natural processes and to forecast what the combined consequences will be. Clearly this is no easy task.

In the past 30 years the world community of scientists through the International Council of Scientific Unions has undertaken a number of broadly based international programs, such as the International Geophysical Year, the International Biological Program, the International Lithosphere Project, and the Global Atmospheric Research Program. These and other major international efforts were each directed at a part of the Earth's environment. A common finding in all these programs was the realization that we must look much more carefully at interactions among parts of the global system if we are to understand the major issues of global change. For example, the World Climate Research Program now includes studies of the ocean, ice, and certain land surface processes. Further understanding requires that we integrate studies of the physical and biological realms to understand the ways in which Earth's living creatures, including man, modify the physical and chemical characteristics of their planetary home and the ways in which Earth's unique physical and chemical conditions in turn determine the development and characteristics of life.

We human beings who are privileged to live on this benign planet can also hope to understand it; indeed, such understanding may well be essential for our survival. The challenge of an IGBP is to gain this understanding by an integrated, global study of the physical, chemical, and biological processes that have produced and now maintain the environment needed for life on Earth.

We urge the following as a focused objective for such a study:

**To describe and understand the interactive physical, chemical, and biological processes that regulate the Earth's unique environment for life, the changes that are occurring in this system, and the manner in which they are influenced by human actions.**

We visualize an IGBP as a tightly defined program of research directed at providing the body of knowledge needed to assess the near-term--perhaps 100-year--future of the Earth. The adoption of this time scale for program emphasis provides another key element of focus, directing the effort at an array of emerging issues that promise most to affect the course of life in the ensuing century.

The purposes of the program would be both fundamental and

practical. A better description and a deeper understanding of the planet on which we live will provide the bases for rational management of resources and at the same time will improve the reliability of warnings of significant global change.

Such an effort, planned now, could begin in the 1990s--a significant period of projected change during which we can expect the first observable climatic impact of increasing CO<sub>2</sub>, the continued depletion of much of the tropical forest reserve, and increasing use of resources by an expanded world population. The long time scales of many of the processes involved as well as the magnitude of the task dictate that an IGBP of this nature should continue well beyond the dawn of the next century. Such a program would be based on a well-planned series of observations and modeling and process studies. It should also include increased efforts to recover a much longer history of the Earth and its environment, from geological records and the records preserved in trees and ice, for we recognize that changes on a wide range of time scales, from years to hundreds of millions of years, are a significant feature of Earth history. Knowledge of the past is essential to the tasks of understanding the present or predicting the future. We envisage an IGBP as a program of cooperative efforts of varied disciplines--with *biospheric interactions* as the focus and discriminator in setting priorities and principal emphases. These critical linkages between living and nonliving components, involving physical, chemical, and ecological processes are in our view the outstanding unknown in our present understanding of the Earth as a system.

In concentrating on the *interactive* areas of the physical, chemical, and biological realms we of necessity put less emphasis on studies that, though they have great strengths and momentum of their own, would less clearly contribute to our understanding of the changing nature of the environment of life. *Priority in an IGBP of this design would fall on those areas of each of the fields involved that show the greatest promise of elucidating interactions that might lead to significant change in the next 100 years, that most affect the biosphere, and that are most susceptible to human perturbation.*

An IGBP that would satisfy such a need should take full advantage of the modern ability to study the Earth's surface, oceans, biota, and inputs from the Sun from the vantage of space. Indeed the new technologies of spaceborne instrumentation and of high-speed computers allow, for the first time, the global synthesis of information needed for scientific understanding. These new technologies are central to advances in such fields as oceanography, geophysics, atmospheric dynamics, and solar-terrestrial physics. But an IGBP cannot be based on space techniques alone. It would demand an even larger observational effort from the ground, on land and sea and ice, as well as from supporting

aircraft. A part of this ground-based effort would be needed to validate and calibrate spaceborne measurements, but a larger part would be devoted to local studies of biomes and climatic zones in selected land or water regions.

An IGBP must be truly international, for the concerns of the program are those of the entire globe. Considerations of access alone will require the participation of scientists and technicians from both the advanced and the developing countries representing all areas of the world. But a need equally great is that of the active *involvement* of the nations and the governments that must ultimately use the knowledge gained to make economic and policy decisions.

A charge to our Committee was to define a number of specific areas of study that could be put forth as typical or exemplary of an IGBP and that would particularly benefit from an international effort and a multidisciplinary approach. In ensuing chapters we explore five such areas and offer preliminary suggestions for program elements that should be undertaken to further understanding in each of them. In Chapter 7 these suggestions are brought together and summarized. At this stage of general definition we have made no attempt to define the details of a final program. Individual elements that might eventually form an IGBP will need to be more thoroughly studied and more explicitly defined by a larger number of specialists who have particular interests in the problems involved and expertise in the techniques of measurement and analysis required. This could be completed in a carefully planned series of international workshops over the next two years. These workshops could be organized through ICSU and coordinated by the *Ad Hoc Planning Group on Global Change* that was recently established by that body. Particular care should be taken in selecting workshop topics to ensure that their aims are a needed part of a cohesive and focused program. Reports of these workshops should propose a timetable of specific recommendations for action.

The problem areas that we recommend for inclusion in an IGBP are as follows:

- o *The Recovery of the Past History of Environmental Change*, involving studies of ocean and earth sediments, ice cores, tree rings, coral deposits, and sea-level changes for what they tell of past climate, ocean circulation, solar inputs, distribution of plants, and chemistry of the atmosphere, earth, and oceans.

- o *Changes in the Current Physical Environment*, involving the observation and understanding of fundamental phenomena of the Sun and near-Earth space, the atmosphere, snow and ice, oceans, and the soils and land surface of the Earth, as well as progress in the development of comprehensive, coupled models of the whole environment. We recognize

that some of the needed research is already being undertaken under the World Climate Research Program sponsored jointly by the World Meteorological Organization and ICSU.

o *Global Changes in the Biosphere*, involving efforts to initiate a study of global ecology, an assessment of the Earth's metabolic capacity, an inventory of changes in biota, and an investigation of the role and effects of human activities in altering the number and distribution of plant and animal species.

o *Global Biogeochemical Cycles*, involving the study of biogeochemical cycles of carbon, nitrogen, sulfur, phosphorus, and other essential elements and compounds in the atmosphere, solid Earth, oceans, and biota.

o *The Global Hydrologic Cycle*, with emphasis on the reservoirs and fluxes of water, their coupling with plant life and biogeochemical cycles, and definition of the impacts of modern agriculture and industry.

The questions involved in each of these are urgent, fundamental, and hard. They are *urgent* because of the necessity to meet the needs and respond to the aspirations of the large human population that will live on the Earth within the next century. They are *fundamental* because they involve understanding of the Earth as a whole and the functioning of interacting forces and complex processes under changing conditions. And they are *hard* because they require that most difficult of scientific enterprises--interdisciplinary comprehension and collaboration--and they must be studied on the Earth as a whole, requiring international scientific cooperation. Their solution, in our view, requires the scope and approach of a dedicated international program. Such an effort, though long needed, could not have been mounted 20 years ago or even 10 years ago. Nor can it be completed in the next 10 years or the next 20. But it must be begun, and the time to make a beginning is now. That we can start today stems from our new-found ability to observe and comprehend the complexity of the Earth on all spatial scales--from atomic to planetary--and, equally new and necessary, our capability through worldwide computer access to manage and disseminate the vast amounts of data that need to be acquired.

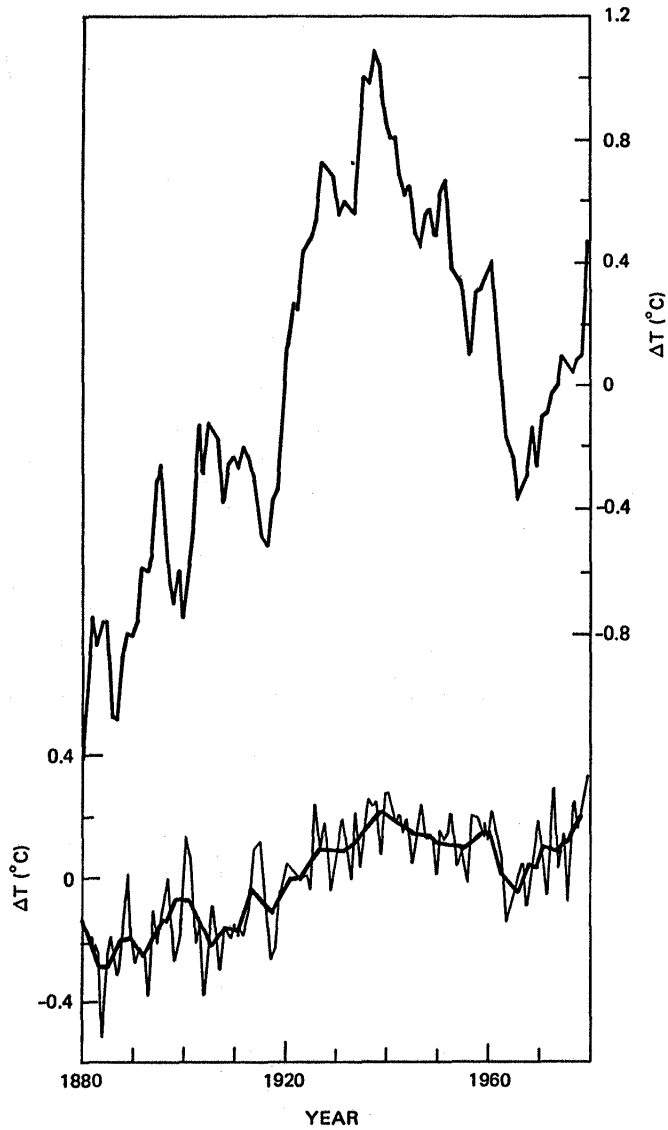
## 2 RECORD OF ENVIRONMENTAL CHANGE

### INTRODUCTION

Environmental change is a fact of life, and one that is felt on all times scales. For example, meteorological station records compiled during the past century show that the global temperature rose during this time by about  $0.5^{\circ}\text{C}$  (Figure 2.1). In high northern latitudes the warming was three times greater. During the 1940s and 1950s, however, the trend of northern hemisphere temperatures turned downward--so sharply that concern was expressed at the time that the world might be heading into a new Ice Age. The nature of the trend in the most current measurements--since about 1960--is now being watched with particular care: Does it signal, like the first robin of spring, the onset of steep warming now anticipated from increasing global  $\text{CO}_2$  and other greenhouse gases?

Two lessons can be drawn from our meteorological experience over the past century. The first is that satisfactory predictions are not safely made by extrapolating past trends. They can come only from a knowledge of the driving forces involved. The second lesson is that environmental changes occur on a hierarchy of time scales. Year-to-year oscillations of the 1940s and 1950s, for example, are superimposed on a 20-year cooling trend, which in turn modulates a 100-year warming trend that is a ripple on a complex of longer cycles of oscillation between glacial and interglacial epochs. Our ability to forecast the future or to assess any of the impacts of human activities rests critically on our knowledge of the processes that lie behind trends occurring on a wide range of time scales. A reliable record of past environmental changes can enlighten the development of environmental models and provide needed tests and constraints.

We now have in hand from paleoclimatic research a reasonably good picture of the main climatic events and trends of the past half million years that are most relevant to IGBP objectives. From a variety of sources we have reasonably good histories of glacier extent, global ice volume, surface ocean temperature, atmospheric  $\text{CO}_2$  content, vegetative cover, lake levels, and soil types. The stage is now set for an intensive



**FIGURE 2.1** Measured surface temperature trends in degrees Celsius for the period 1880-1980 as a global mean (lower curves, annual and 5-year running mean) and for stations poleward of latitude  $64^{\circ}$  N (upper curve, 5-year running mean). After J. Hansen *et al.*, 1983.

look at the dynamic content of these records. What forces induced these changes? What feedback mechanisms were at work?

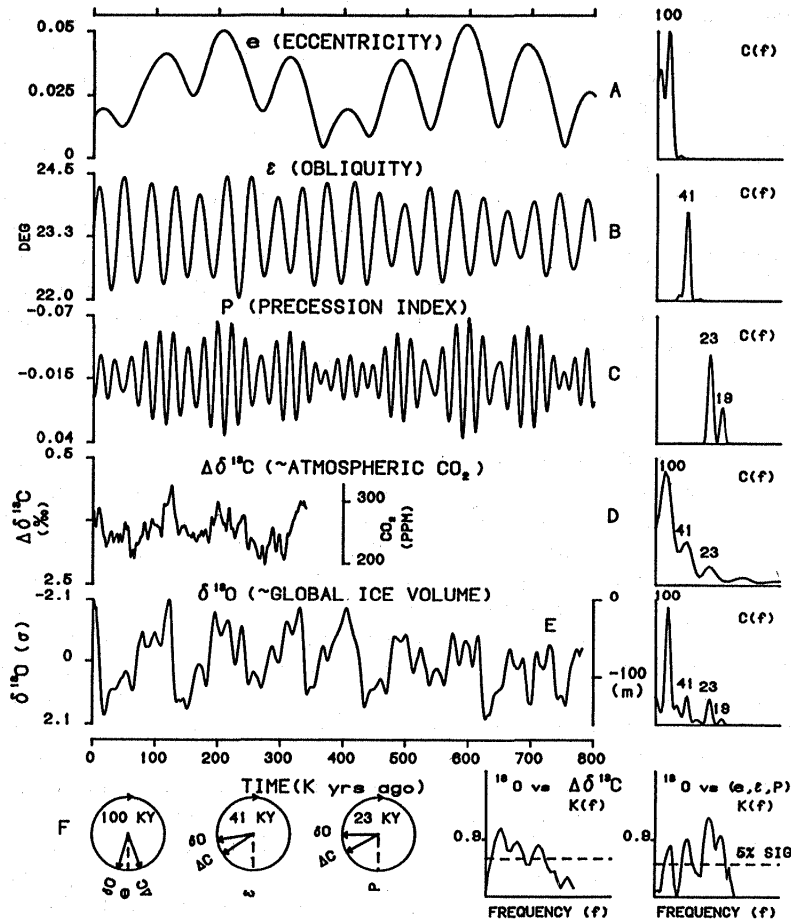
To answer these questions requires rigorous study of continuous records that contain quantifiable environmental indicators such as isotope ratios, chemical ratios, species ratios, and accumulation and deposition rates. Four types of natural history hold the most promise for these ends: the records kept in sediments, ice caps, tree rings, and coral deposits. These natural diaries provide individual and different insights into the past history of the Earth; each covers a characteristic span of time, and each has a different temporal resolution. Here we consider the principal records in turn, illustrating the kinds of insights that have been provided and assessing the promise that each of them holds for an IGBP. We begin with the sediment record, not because it necessarily holds the most promise but because it is the longest and thus provides the clearest perspective of global change.

## SEDIMENTS

Environmental records that span half a million years and more are all dominated by dramatic swings between glacial and interglacial stages. The marine sediment record makes it clear that the benign global climates that characterized the past 10,000 years (the Holocene Epoch) are but the interglacial phase of an ongoing glacial-interglacial cycle (Figure 2.2E). Only 18,000 years ago, our ancestors lived in an ice-age world, with ice sheets covering all of Canada, part of the United States, and much of Northern Europe, with sea level some 60 to as much as 140 meters lower, and with a climate much cooler and drier than today. From sediment records on land comes evidence that the pattern of ice-age vegetation in temperate North America was very different from that of today--and a clear picture of how the vegetation responded during the past 18,000 years to a continually changing climate (Figure 2.3).

Two important conclusions can be drawn from these sedimentary records. The first and perhaps more important is that global ecosystems are never static. Communities of animals and plants continually shift in response to changes in their physical environment. As every species now alive must be adapted to survive diurnal and annual cycles of environmental change, so every enduring species has also adapted to endure the range of conditions encompassed in the much longer cycles of glacial-interglacial succession. A second conclusion is that the Earth's climate system appears to be surprisingly sensitive to small changes in external boundary conditions. The natural factors that pace the most dramatic climate variations known--the glacial-interglacial succession--are subtle changes in the seasonal and latitudinal distribution of sunlight. These changes, which for any latitude are no more than about  $\pm 5$  percent, are in turn the consequence of small, secular variations in the orbit of the Earth about the Sun (Figure 2.2, Panels A, B, and C).





**FIGURE 2.2** Changes in the orbit and climate of the Earth during the past 800,000 years. Time series in rows A-C (left) are variations in the eccentricity of the orbit, the obliquity of the ecliptic, and an index of the climatic effect of precession  $P = \Delta e \sin \omega$ , a measure of the Earth-Sun distance on June 21) as calculated by Berger (1976). The corresponding spectra display variance density ( $C$ ) as a function of frequency; the dominant periods of conspicuous peaks are labeled in thousands of years (kyr). These orbital variations cause changes in the seasonal and latitudinal distribution of incoming solar radiation that are on the order

of  $\pm 5$  percent for particular latitudes and seasons; the total annual income is nearly constant. The time history of these radiation anomalies is a strong function of latitude and season.

The time series in row E is a set of oceanic  $\delta^{18}\text{O}$  observations obtained by averaging planktonic data from five widely separated deep-sea cores. Variations in this curve are highly correlated with changes in the global volume of glacial ice; an approximate scale of equivalent sea-level change is given at the right (meters); the scale at the left is in units of standard deviation ( $\sigma$ ). Significantly, the spectrum of this time series (Row E, right) has concentrations of variance at the same periods that dominate orbital history: 19 kyr, 23 kyr, 41 kyr, and 100 kyr. In each of these narrow frequency bands, moreover, the isotopic variations display a high degree of linear correlation ( $r \sim 0.9$ ) with variations in one of the orbital curves, as shown by the coherency spectrum (Row F, far right). As shown by the phase diagrams (Row F, left), the variations in  $\delta^{18}\text{O}$  lag significantly behind orbital variations in each frequency band. This would be expected, given the long time constants of ice-sheet growth and decay ( $\sim 15$  kyr). This statistical evidence of a close relationship between the time-varying amplitudes of orbital forcing and the time-varying amplitudes of the  $\delta^{18}\text{O}$  response implies that orbital variations are the main external cause of the succession of late Pleistocene ice ages (Imbrie *et al.*, 1984). This conclusion is strongly supported by numerical experiments with climate models (Kutzbach and Otto-Bliesner, 1982; Kutzbach and Gietter, 1984; North *et al.*, 1983).

The time series in row D (left) are observed differences in  $^{13}\text{C}$  concentration between surface and deep-dwelling foraminifera, expressed as  $\Delta\delta^{13}\text{C}$  (parts per mil). This high-resolution (6 cm/kyr) record was obtained from a deep-sea core at an eastern Equatorial Pacific site (Shackleton *et al.*, 1983; Shackleton and Pisias, in press). Based on a model advanced by Broecker (1982), the same authors have argued that an increase in the vertical oceanic  $^{13}\text{C}$  gradient reflects an increase in the proportion of upwelling carbon removed by photosynthesis and that such an increase is associated with a decrease in the concentration of  $\text{CO}_2$  both in the surface ocean and in the atmosphere. The right-hand scale is an estimate of atmospheric  $\text{CO}_2$  concentration (ppm). Significantly, the (low) estimates of atmospheric  $\text{CO}_2$  during the last ice age that were obtained in this way agree with independent estimates obtained earlier from bubbles in Ice Age ice (Neftel *et al.*, 1982).

The spectrum of this carbon isotope time series (Row D, right) has concentrations of variance at three of the same periods that dominate the orbital and  $\delta^{18}\text{O}$  records (23 kyr, 41 kyr, 100 kyr). Moreover, the  $\Delta^{13}\text{C}$  and  $^{18}\text{O}$  records are highly coherent at these frequencies (left-hand coherency spectrum, Row F). Significantly the phase diagrams (Row F, left) show that changes in  $\delta^{18}\text{O}$  lag systematically behind variations in  $\Delta\delta^{13}\text{C}$ . This suggests that the concentration of atmospheric and oceanic  $\text{CO}_2$  varies in response to orbital forcing (by mechanisms yet to be

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Recent evidence suggests that one of the major *mechanisms* by which the climate system responds to these subtle forcings involve global changes in the carbon budget (Figure 2.2D).

Although much effort has gone into the study of isotopic and biotic records in deep-sea cores, many important problems remain to be solved. Notable among these are problems of reconstructing the circulation patterns and nutrient chemistry of the oceans. Detailed geochemical measurements of cadmium and of  $^{13}\text{C}/^{12}\text{C}$  ratios in foraminiferan shells, of calcite dissolution indices, and of indices related to bottom water  $\text{O}_2$  content are needed to understand the circulation of the paleo-ocean and its impact on regional climates and on atmospheric  $\text{CO}_2$ . Atomic accelerator analysis of minute amounts of carbon now make it feasible to measure  $^{14}\text{C}$  in co-existing surface and bottom-dwelling foraminifera, and this offers an opportunity to establish paleo-ocean ventilation rates during the past several tens of thousands of years.

Finally, the record of pollen, dust, and ice-rafted material in sediments from the margins of the sea must be studied to establish a correlation with continental climatic events, with particular attention to sediments from high latitudes. The techniques of spectral analysis can now be applied to assess the importance of astronomical cyclic forcing of climate and to correlate cores from different geographic regions. Joint efforts similar to those now being conducted by the NSF Cooperative Holocene Mapping (COHMAP) and Spectral Mapping (SPECMAP) groups should be encouraged.

In addition to marine sediments, far more attention must be given to sedimentary records from lakes and other inland bodies, and particularly in lakes that existed during glacial times. To date these studies have focused chiefly on the floral transition that followed the end of the last glacial period. The possible finding in Greenland ice of discrete warm events of about 800 years' duration 45,000 to 25,000 years ago clearly calls for a careful search for these events in continental records covering the same interval. The  $^{14}\text{C}$  content of older lake sediments can be used also to estimate atmospheric  $\text{CO}_2$  concentrations in past times.

Studies of sediments formed in lakes, bogs, and river terraces have much to offer regarding the history of man's full impact on the environment. For example, records of sediment accumulation rates provide one way of assessing the extent to which natural soil erosion rates have been modified. The study of the amount and distribution of pollen grains offers a powerful means of determining changes in

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discovered) and that these changes are part of the complex of mechanisms which make the Earth's climate system so sensitive to the relatively modest orbitally driven changes in the radiation budget.

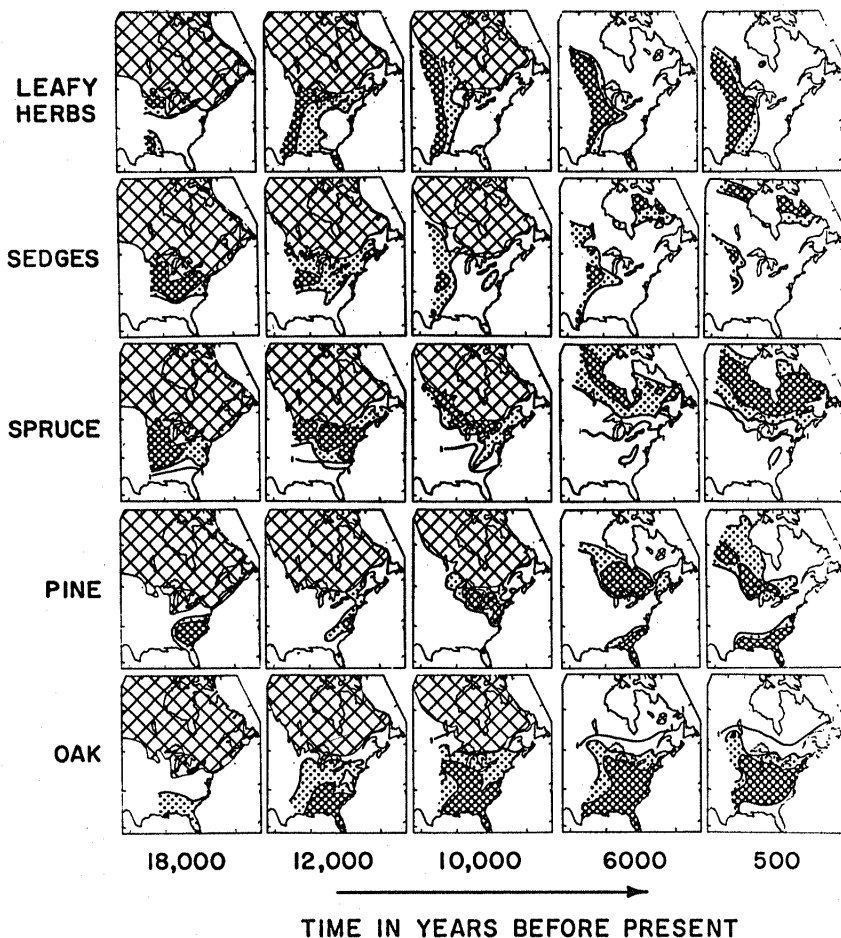
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vegetational distribution; moreover, the charcoal content of sediments indicates the frequency of forest fires, and the metallic content records the flux of airborne pollutants.

### ICE CORES

The history of past climate is nowhere better preserved than in the ancient ice of Greenland and Antarctica. These valuable deposits, some as thick as several kilometers, preserve the fallen snow for several hundred thousand years. The list of measurable properties is already long and growing rapidly. Annual increments of local precipitation are directly obtained, and annual seawater temperatures are now routinely derived through analyses of  $^{16}\text{O}$ : $^{18}\text{O}$  and H:D ratios. In addition, the chemical and solid fallout, the  $^{10}\text{Be}$  content of the ice, and the  $\text{CO}_2$  and  $\text{CH}_4$  content of entrapped air have all been studied. Each of these records has revealed an astounding encoded message, and each has given us powerful new insights into past environmental change. They show, for example, that  $\text{CH}_4$  has doubled in the air since A.D. 1600 through sources of production that are yet unknown. They show that the  $\text{CO}_2$  content of the air was 30 percent lower during glacial time than in the Holocene. They show that the polar atmosphere was far dustier during glacial interludes, implying a possible, significant connection between atmospheric turbidity and major climatic change. Rates of past deposition of cosmogenic  $^{10}\text{Be}$  in polar ice call into question the canonical picture of variations in the strength of the Earth's magnetic moment in the past 10,000 years that was based on the initial interpretation of secular changes in tree-ring radiocarbon in the same period; the same measurements of iceborne  $^{10}\text{Be}$  promise to open new vistas on the behavior of the ancient Sun. Ice-core analyses provide direct measures of the change in polar temperatures between glacial and interglacial epochs. They indicate that very rapid changes in climate may have occurred during glacial time, leading to the suggestion that the Earth may operate with more than one mode of ocean-atmosphere interaction.

By examining the acidity of ice cores, it is possible to recover a temporal history of the atmospheric concentration of acid aerosols at high latitudes. There is good evidence that this record primarily registers the volcanic flux of sulfate particles whose increase is known to affect the Earth's radiation budget so as to induce global cooling. In this way the ice-core record provides not only a quantitative record of explosive vulcanism that can be compared with other geologic records but also an enhanced ability to assess the role that such activity plays in altering global climate.



**FIGURE 2.3** Vegetation change in eastern North America during the past 18,000 years from full glacial conditions (18,000 years ago) until just before European settlement (500 years ago). Cross-hatched area is the ice sheet. Areas with heavy stippling (HS) and light stippling (LS) show regions with different concentrations of pollen types, expressed in percent of the total pollen rain observed at fourteen 18-kyr sites, fifty 12-kyr sites, and over two-hundred sites at younger times. The distribution of *leafy herb* and *sedge* pollen (>5%, LS; >10%, HS) represents various types of prairie, tundra, and open woodland vegetation. The distribution of *spruce* pollen (>5%, LS; >20%, HS) indicates the development of spruce woodlands and (since 6000 B.P.) the boreal forest. The changing

Exploitation of the ice-core record has only begun. By judicious choice of drilling sites, older ice can be reached that allows the study of full cycles of glaciation--far beyond the currently available span of about 75 percent of the most recent major oscillation. More precise dating can be accomplished through  $^{14}\text{C}/^{12}\text{C}$  and by  $^{10}\text{Be}/^{36}\text{Cl}$  ratio measurements using accelerator mass spectrometry by taking advantage of the differences in half-life of these and other isotopes. It should be possible to secure continuous records of abundances of greenhouse gases, the  $^{13}\text{C}/^{12}\text{C}$  record for atmospheric  $\text{CO}_2$  and  $\text{CH}_4$ , the influx rates of the cosmogenic isotope  $^{10}\text{Be}$ , and long-term records of explosive vulcanism. A high-priority item in an IGBP should be efforts to strengthen and expand the existing international ice-core drilling programs and to widen participation in laboratory studies of this unique record. Cores from West Antarctica, where ice as old as 500,000 years may yet survive, may help to answer whether the West Antarctic ice cap disappeared during the last interglacial, as suggested by the existence of a 6-meter terrace in shorelines in many parts of the world that can be dated at 125,000 years ago.

### TREE RINGS

Trees are compulsive diarists. The thickness of wood in an annual tree ring provides a direct measure of growth in that year, and hence of local environmental conditions. For some applications seasonal resolution can be obtained by analysis of early and late wood in a single ring. In many areas of the world, such records can be extended back several hundreds of years, and in some cases several thousand years. The study of tree rings, therefore, provides unique insights into the history of our environment--and with one-year resolution. Records of this kind will clearly become more important as we attempt to assess, for example, the impact of acid rain and increase in carbon dioxide. To illustrate how

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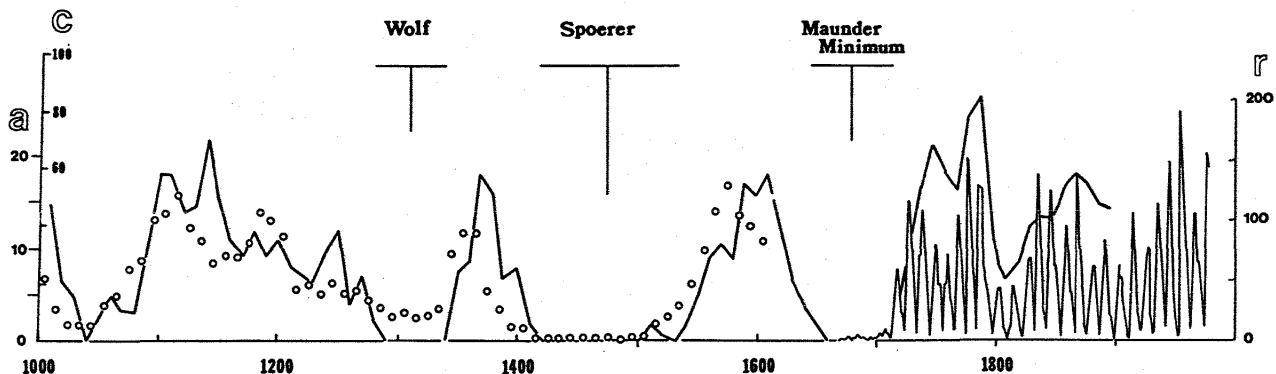
distribution of *pine* pollen (>20%, LS; >40%, HS) represents the northward movements of northern pine forests from South Carolina and Georgia to the Midwest, and the recent development of the southern pine forests. The distribution of *oak* pollen (>5%, LS; >20%, HS) reflects the extent of deciduous forest. Note that the regional vegetation pattern is always changing in response to natural changes in radiative and climatic boundary conditions. A particularly rapid change in vegetation, ice volume, and climate occurred between 12,000 and 10,000 years ago (coinciding with a maximum in northern hemisphere summer insolation), whereas the major change in the area of the North American ice sheet occurred later (unpublished pollen data from the COHMAP project; ice margins derived from Mayewski *et al.*, 1981).

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important such studies may be, we cite a recent large-scale analysis of growth trends in subalpine conifers in the western United States. This study finds evidence of a systematic increase in ring widths since the middle nineteenth century that is consistent with the enhanced growth expected from the known increase in global carbon dioxide. The increase, of more than 70 percent in California samples, seems unrelated to local climate. Whether that is so is subject to question. But if carbon dioxide is indeed the cause, it provides key information on the response of biota to anticipated increases in atmospheric  $\text{CO}_2$ .

Tree-ring samples that predate the era of instrumented weather records are available from almost all temperate regions. For this reason, studies of ring widths and wood density have been extensively used to reconstruct histories of river flow, drought, air temperature, and, through multivariate analysis, of atmospheric pressure and circulation patterns. This information, when combined with studies of the chemical composition of the cellulose itself, provides a revealing record of past environmental change. Ring-by-ring analyses of stable isotope ratios of H/D,  $^{18}\text{O}/^{16}\text{O}$ , and  $^{13}\text{C}/^{12}\text{C}$ , for example, provide a measure of tree temperature and metabolism. Moreover, through their photosynthetic intake of carbon dioxide, trees take up atmospheric radiocarbon that is formed in the high atmosphere through the impact of high-energy galactic cosmic rays. The analysis of  $^{14}\text{C}/^{12}\text{C}$  ratios in dated wood tells us much of what we know of the past history of radiocarbon production and hence about the history of cosmic ray fluxes at the orbit of the Earth (Figure 2.4). From these data has come a 7500-year record of solar activity and possible information on climate, the carbon cycle, and the varying strength of the Earth's magnetic field. The comparison of tree-ring radiocarbon variations with cosmic-ray-induced  $^{10}\text{Be}$  in ancient ice offers the hope of disentangling the convolved histories of solar-magnetic-field variations, geomagnetic changes, and climatic effects. The most recent 350 years of the tree-ring radiocarbon record overlaps the era of telescopic observation of the Sun; comparison of the two reveals an almost identical picture of solar behavior, thus providing a reliable template for interpreting the earlier radiocarbon data that extend to the time of the late Stone Age. This long tree-ring record comes from the bristlecone pines that live as individual specimens for as long as 5000 years. Older, undated samples of wood have been found that evidently come from late glacial time. Because of their acute environmental sensitivity, tree rings offer our best hope of recovering the history of climate of the continents over the last several thousand years.

Although the tree-ring record offers great promise, its interpretation is extremely complex. If we are to learn to read it properly, a considerable effort will have to be made. An expanded but judicious



**FIGURE 2.4** Three indices of solar activity compared as a function of time for the period since A.D. 1000. The observed annual mean sunspot number ( $r$ , scale at right, from Eddy, 1976) is shown by the thin line beginning in A.D. 1650, with pronounced 11-yr cycles visible after about A.D. 1700. The heavier curve ( $c$ , scale at left) extending from A.D. 1000 to A.D. 1900 is a proxy sunspot number index derived by Stuiver and Quay (1980) from their measurements of tree-ring  $^{14}\text{C}$ . As a proxy it successfully replicates the envelope of observed sunspot number ( $r$ ) in the period of overlap—which ends about 1900 owing to the overwhelming presence of fossil-fuel carbon in tree rings after that date. Open circles ( $a$ , scale at left) are an index of the occurrence of northern hemisphere aurorae, another measure of solar activity, in sightings per decade (from Eddy). The three independent indices confirm the existence of significant, long-period changes in the level of solar activity, including three prolonged periods of depressed behavior labeled as the Wolf, Spoerer, and Maunder minima.



sampling of the tree-ring sites must be undertaken, and in often remote areas of the world where environmentally sensitive species are found. In addition, growth-chamber experiments and purposeful field experiments will have to be conducted to improve our knowledge of the response of trees to various stresses. An IGBP will call for a considerable expansion of the existing modest effort in this area.

### CORAL DEPOSITS

The production of calcium carbonate in the shells of mollusks and in corals is a function of local conditions, and hence another potential source of environmental history. Moreover, these shells and deposits, which are recoverable in fossil form, have been demonstrated to grow in many cases in discrete annual and even daily steps, offering environmental diaries of unusual temporal resolution. Attempts to read and exploit this potential source of Earth history have been limited chiefly to the coarser coral record.

One aspect of the coral record requires special attention. World sea level is expected to reflect long-term changes in mean global temperature through changes in the storage and release of water in polar and other ice reserves. As noted earlier in this chapter, the argument has been made that raised coral reefs with radiometric dates of about 125,000 years found, for example, on Bermuda, Australia, the Bahamas, and Hawaii, demonstrate that the world sea level stood about 6 meters higher at the time of the last interglacial maximum. The source of the extra water is conjectured to be the melting of the predecessor to what is now the West Antarctic ice sheet. The implication drawn is that the global warming now expected from increased fossil fuel CO<sub>2</sub> in the atmosphere could cause a repeat of this phenomenon. Related to this argument, however, is the question of whether the coastlines where uplifted corals are found were themselves subjected to a few meters of tectonic uplift during the same period, thus altering the reference of measurement. A more extensive study of coastal contours must therefore be made in these regions, to determine whether on these coasts there exist the subsiding counterparts of those elements on which raised corals are found. If so, it may imply that sea level stood no higher during the last interglacial than it does today. The question is one of such fundamental importance that it demands resolution. The international and multidisciplinary features of an IGBP would lend themselves well to such a study.

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### 3 THE ENVIRONMENT FOR LIFE

#### INTRODUCTION

We all experience to some degree the consequences of change in our physical environment. Often they are adverse. For some it is the destruction of property by a flood; for others, the disaster brought about by prolonged drought. For still others it is the decline of agricultural productivity through soil impoverishment, the depletion of coastal fisheries, or the damaging of lakes and trees by acid rain or by other air or water pollution. Some of these changes are natural and recurrent; others may be attributed to the hand of man, as the consequence of his ever-increasing presence on the globe. To anticipate global changes, including those induced by man, we need to understand their causes and natural variations; yet in this endeavor we often deal with interacting and synergistic processes that are beyond the scope of isolated physical or biological studies.

International concern over long-term global environmental changes arises in part from the realization that the impacts of man's activities are not always confined to the area in which the primary intervention arises. For example, much of the chemical effluent released to the atmosphere from heightened industrial smoke stacks--installed to solve local problems--now passes across state and national boundaries where it can reach the ground as acid rain. Similarly, although  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ , and halocarbons are introduced locally and unevenly into the atmosphere, their consequence is now predicted to be global climatic changes whose potential impacts we are just beginning to grasp. We are also concerned that man-made dust may play a role in changing the planet's climate and that the diversion of rivers for irrigation may significantly change the large-scale patterns of evaporation and rainfall.

We know that, quite independent of human intervention, the environment has changed substantially over a wide range of time scales in the past, and there is no reason to think that similar changes will not recur. Some of these changes--such as tropical cycles of dry and wet or the astronomically paced Ice Ages and the associated shifts in the distributions of animals and plants and soil features--occur so slowly that

they will have little detectable impact in the course of the next century. At the other end of the spectrum are natural climatic events that occur on time scales from a year to decades. Most notable among these is El Nino, which introduces abrupt and dramatic changes in the circulation of the tropical oceans and of the global atmosphere and which appears to be driven by strong interactions between the atmosphere and ocean. Another, less predictable example, is that of explosive vulcanism and resultant global cooling. Between these extremes are the largely unexplained climatic events whose durations are measured in centuries, such as the Little Ice Age of about A.D. 1500 to 1850, or the recurrent warming episodes, each lasting a millennium or less, that appear to have punctuated the most recent major glaciation.

As discussed in the preceding chapter, we are only now learning to read the record of these events in tree rings and ice cores and other natural diaries, and it is essential that we achieve a better understanding of the range and course of natural variability on all time scales. Until we develop a more thorough knowledge of the natural background of change in the physical and chemical environment and the processes of feedback and interaction, we have little hope to isolate and identify the impacts of man's intervention.

### *Finding a Solution*

Three major approaches must be taken if significant progress is to be made:

- o The taking of synoptic *observations* directed at illuminating the way in which present environmental systems operate. These observational programs will require satellites orbiting the globe, ships traversing the world's oceans, and field stations on the ground--some in remote regions of the globe.

- o Directed efforts to understand the *past record of environmental change* contained in meteorological records or preserved in tree rings, ice, geologic strata, and in the sedimentary layers of lakes, bogs, and the seafloor. As noted in Chapter 2, these records provide our main source of information about the natural variability of the environment and the role of external inputs to the system, such as solar and geomagnetic variations. They also yield important insights into the effects of natural feedback mechanisms that can amplify man's impacts on the environment. Since we cannot perform field experiments of global scale and geologic duration, we must make every effort to utilize the record of experiments already conducted by Nature.

- o The development of new *models* of the coupled environmental system. Dynamical models currently used for weather forecasting, general circulation studies, and climate simulation now include many of

the important physical processes at work in the atmosphere. The new challenge is to create coupled physical, chemical, and biological models for the environment as a whole. To do this will first require major improvements in the manner in which processes such as cloud formation and precipitation and factors such as sea ice and soil moisture are handled by atmospheric models. The interpretation of these data will also require the development of fully interactive ocean-atmosphere-land surface models that include wind- and density-driven (thermohaline) ocean circulation and the formation and melting of sea ice. Models of this kind will need to include the effects of chemical changes in the atmosphere and more realistic parameterizations of vegetation, since this variable component of the environment interacts profoundly with the heat and moisture budget of the land surface. It is safe to say that if we are to gain a reliable and comprehensive assessment of the environmental consequences of human activities, it must come ultimately from such models.

#### OBSERVATIONAL PROGRAMS

The greatest impediment to more reliable prediction of environmental change is our lack of understanding of many physical and chemical processes that are key to the operation of the current atmospheric, oceanic, and biospheric systems. In most cases existing observations have been worked and reworked to the extent that little more new insight can be expected. As is so often the case in science, significant advances await new observations. For some problems we have a clear idea of which data sets are critical; in these, progress awaits resources to launch satellites, to operate an ocean survey or to install a set of ground-based monitoring stations. In other cases it is not yet known which of several available measurement strategies will provide the hoped-for advances. Since global observational programs are costly in both time and manpower, great care must be taken in deciding which strategies to implement and which experiments should be conducted.

Since new observations will form the basis of any geosphere-biosphere program, it is important that the best possible strategies be agreed on and implemented. Many of the feasible strategies have already been proposed and discussed as multidisciplinary initiatives in the World Climate Research Program. The programs suggested here are meant to build upon these existing and planned efforts, which indeed address many of the physical aspects of the global atmosphere and its interaction with the ocean. The initial job of an IGBP is to identify other promising options for understanding the working of the Earth as a system. Here we cite some examples of observational programs that we believe necessary for our understanding of the operation of individual environmental systems and that are critical to our understanding of important linkages.

*Observations of the Sun*

Essential to life is the continuous energy of sunlight that warms the Earth and oceans, stirs the air, and forges through photosynthesis the first essential links in the food chain. The bulk energy or integral of radiative energy of the Sun, centered in the visible and near-infrared wavelengths, serves as the principal driver of atmospheric circulation and thus, in a sense, powers the climate machine. The march of the seasons is ample evidence for the acute sensitivity of the environment of the Earth to changes in the distribution of solar radiation. A more sensitive gauge of the Sun's impact on climate, however, is found in the Milankovitch effect, by which slow and subtle changes in the latitudinal and seasonal distribution of insolation, smaller than seasonal variations but of much longer period, serve to pace the recurrence of major Ice Ages and other long-term climatic cycles. Solar ultraviolet radiation, rising and falling with solar activity, dictates the basic chemistry of the upper and middle atmosphere, including the equilibrium and balance of important trace gases such as ozone. The possible influence of atmospheric electricity on climate, atmospheric chemistry, and the biosphere is an intriguing question that has received little quantitative study. The potential of the global electric field is maintained by thunderstorm activity, but it may be perturbed by solar-induced variations in cosmic ray flux or by changes in the efficiency of coupling between the solar wind and the high latitude ionosphere.

Each of these inputs has played a role, and often a crucial one, in setting the conditions for life on Earth, and every one of them is variable, over a range of variation that is now only crudely known.

The solar inputs to the Earth are today sufficiently steady that they are often taken as constant. In reality none of them is. Far and away the most energetic of inputs, the so-called "solar constant" (or integral of radiative flux at mean Sun-Earth distance), is now known to vary, and in several ways. Precision spaceborne measurements, made since 1978, have established that the total solar irradiance delivered to Earth fluctuates daily at the level of 0.1-0.3 percent in step with solar activity, and there is some evidence that it has also been decreasing at about 0.01% per year since these observations began. A change of 0.1% in the total radiative output of the Sun, if maintained for a decade or longer, will alter the surface temperature of the Earth by 0.1-0.2 °C, and possibly by more if enhanced by a number of possible feedback effects, including links with the biosphere. We know nothing at all of solar energy variations on longer time scales. But a persistent change of 1 percent in the solar constant would alter surface temperature by an amount comparable with that currently projected from CO<sub>2</sub> warming in the next 60 years, and a drop of this amount seems more than enough to induce the cooling that gripped Europe and North America in the Little Ice Age, between the sixteenth and middle nineteenth centuries.

While far less energetic than the integral of visible and near-infrared radiation, the solar ultraviolet flux is characterized by greater variation:

these changes, acting through the lever of atmospheric chemistry, can exert an influence on both climate and the conditions for life on the planet.

Continuous measurement of the solar inputs to the Earth is a recent endeavor, spurred by a belated appreciation of their importance and made possible by spaceborne platforms and the development of reliable, precision instrumentation. An unbroken sequence of spaceborne solar-constant measurements is now available for about 6 years from Nimbus 7 and for an interrupted 4 years from the more precise radiometer on the Solar Maximum Mission (SMM) spacecraft. Observations of the *spectral* irradiance, as in the ultraviolet, are more sporadic, as are measurements of the flux, velocity, and composition of the solar wind and in situ probing of the Earth's magnetosphere. Exploratory measurements have revealed the nature of short-term changes and the general response of most of these parameters to sporadic solar activity; but for none of them do we have a definitive description of its quantitative variation in the course of the 11-year solar cycle or even for some of whether such a generalized pattern even exists.

An often-stated goal is that of continuous measurement of each of these fundamental inputs for a full magnetic cycle of the Sun, or 22 years: such a goal is timely and appropriate for an IGBP effort; for it would be most efficiently done, and probably only done, through the cooperation of multinational space programs. The interpretation of these data would also require a program of continuous supporting observations of the Sun from the ground, which are also best accomplished by international coordination. While many of these spaceborne and ground-based measurements would add to our understanding of the Sun and the magnetosphere and their patterns of behavior, their primary value in an IGBP is a definitive description of variable solar inputs to the Earth. Such knowledge is essential if we are to make progress in defining and delimiting the terrestrial impacts of solar variability and of changes in the Earth's electric and magnetic fields on climate and on the evolution of the atmosphere and the evolution and response of the biosphere.

The seat of solar activity lies beneath the visible surface of the Sun. Principal unknowns in understanding the physics of the solar cycle are conditions in the convective zone, including its depth and the scale and physical parameters of convective cells. It is now possible to probe conditions in the convective zone through the technique known as "solar seismology," by which interior conditions are deduced through the analysis of patterns of solar surface oscillations resulting from trapped, subsurface pressure waves. The measurements needed for these analyses are broadband, high-resolution observations of the brightness of the solar surface for continuous periods of at least tens of days. A feasible way to achieve such coverage is through a global, ground-based network of observing stations, requiring international coordination and planning. Eventually, such measurements can be made, more accurately, from above the Earth's atmosphere.

*Atmospheric and Oceanic Observations and Monitoring*

Operational meteorological observing programs now exist to support global weather forecasting and climate research. These include surface, upper air, and satellite observational networks for atmospheric temperature, pressure, winds, radiation, and cloudiness and cloud structure. Under auspices of ICSU and the World Meteorological Organization (WMO) such efforts have been effectively planned and coordinated on regional and global scales, as truly international endeavors. The Global Atmospheric Research Program, which culminated in a year-long program in 1979--the Global Weather Experiment--and the follow-on World Climate Research Program (WCRP), now in progress, are good examples. Of particular importance to an IGBP are data relevant to global environmental change and the monitoring of processes that exhibit a potential for significant biospheric interactions. Long-term records of global surface temperature, the atmospheric radiation balance, and the elements of the surface heat and moisture budgets are already being obtained under the WCRP. Special efforts should also be made to develop and maintain research-quality data sets of global snow and ice mass, surface soil moisture, and concentrations of atmospheric trace gases and aerosols.

The WCRP places special emphasis on the interaction of clouds and radiation and on ocean processes and their interaction with the atmosphere. On the time scales relevant to an IGBP, the planned WCRP World Ocean Circulation Experiment (WOCE) is of particular interest. The primary goal of the WOCE is to understand the general circulation of the global ocean well enough to be able to model its present state and to predict its evolution in relation to long-term changes in the atmosphere. The WOCE is aimed at providing the scientific background for designing an observing system for long-term measurement of the large-scale circulation as a basis for operational climate prediction. This international experiment has as its centerpiece global satellite measurements of variations in ocean level, or surface topography, and of surface roughness. The objective of the surface topography program is to learn more about both the steady-state flow of water through the ocean and the variability in this flow. The objective of the roughness program is to measure the stress exerted on the sea surface by wind. Since wind stress drives surface currents and is involved in the exchange of heat, water, and various gases with the atmosphere, it is critical to define its geographic and seasonal means as well as its variability. In connection with satellite missions, plans have been made to make density sections within the ocean to couple with the surface topography measurements and to make ocean wind observations to aid in calibrating the remote roughness measurements. In addition there are plans for deploying neutrally buoyant floats at various density levels in the sea and plans for measuring the distributions of radioisotope and chemical substances as tracers to define the mean transports of water through the body of the ocean. The distributions of transient tracers such as Freons, radiocarbon,



tritium, and helium-3 are ideally suited for testing general circulation models of the ocean.

### *Geologic Processes*

Programs of observation in the solid earth sciences will represent an integral part of any investigation concerning the interrelationships of the physics, chemistry, and biology of the geosphere-biosphere. Many but not all aspects of geology involve processes that have operated over a time scale of millions--even billions--of years; none the less, short-term (e.g., 1000-year) changes on the Earth represent segments of a temporal continuum, and the orogenic and related physiochemical processes are geologic by definition. Many apparent short-term variations, such as the incidence of volcanoes, earthquakes, and prevalent climatic trends, can only be fully grasped if framed in the context of geologic time and viewed in the perspective of prolonged causative processes such as crustal deformation and the paleoclimatological evolution of the planet.

Equally important, much ongoing geologic activity takes place over time intervals measured in years, decades, or centuries. Neotectonic processes (such as modern land subsidence, elevation changes, deformation, and seismicity), volcanism, landsliding, soil production, and erosion have undergone marked changes that have profoundly influenced the course of life and of civilization. Modern man with his ability to modify the landscape and his growing demands for natural resources (including minerals, water, and fossil fuels) has irrevocably altered superficial portions of the Earth's crust. The siting of critical facilities, the prediction and ameliorization of geologic hazards, and the containment and disposal of toxic waste products have been addressed but not solved.

For civilization to utilize the environment more widely in the next century we will need to understand far better the complex interactions that thread the lithosphere, hydrosphere, atmosphere, and biosphere. Ongoing geologic processes are part of this complex web.

As but one example, volcanic activity--both continental and submarine--can be a major perturber of the environment for life, on local to global scales. Volcanoes deliver sulfur, chlorine, and other chemical species and particulates to the troposphere and to the stratosphere, where residence times are long. Explosive injection of volcanic solids, liquid droplets, and gases to high altitudes in the atmosphere bring about measurable and sometimes dramatic changes in the turbidity and chemical properties of the global atmosphere. These changes can act to reduce the surface temperature of the Earth for periods of one to several years until diffusion clears the air, as demonstrated in analyses of station weather records following the major known volcanic events of the past century. The record of mountain glacier oscillations suggests a possible connection with episodes of volcanic activity that would identify explosive vulcanism as a major perturber of world climate.

What is less known are the detailed physical, chemical, and

dynamical processes through which volcanic ejecta modify the three-dimensional atmosphere, the relative and related roles of gases and particulates, and a more complete and quantitative history of past events. Added to this is the even more fundamental need for improved comprehension of vulcanism itself, leading to the ultimate goal of reliable prediction of these and other related seismic events. This will entail individual observations and measurements, the establishment of observing networks to make opportune use of natural events, and a close alliance with ongoing programs such as the International Lithospheric Study.

#### *Measurements of Soil Moisture, Chemistry, and Soil Dynamics*

Global measurements of soil moisture are needed both for climate models and for estimating the productivity of farms, forests, and grazing lands. Such measurements can best be accomplished by a combination of spaceborne and ground-based sensors. There are a number of techniques that can be employed for remote measurements. Microwave sounding of the top few centimeters gives information on recent wetting. Measurement of the thermal inertia of bare soils can distinguish soils with considerable water from those in which most of the water has been depleted. Infrared soundings of surface temperatures can be used to distinguish plant canopies suffering water stress from those well supplied with water. Near-infrared reflectance measurements will also distinguish hydrated plant tissue from that which is nonhydrated.

What is needed is a practical global observing system for soil-moisture measurement in a number of carefully selected, representative regions. This should include:

- o Inventories of soils and their water holding characteristics.
- o Inventories of vegetation cover with consideration of season, stage of growth, and plant vigor.
- o Data from closely spaced networks of ground-based precipitation sensors and/or ground-based, airborne and space-based radars.
- o Data from similar networks of microclimate stations providing information on net radiation, air temperature, vapor pressure, and windspeed.
- o Regional measurement and study of the physical and biological processes that control evapotranspiration.

For global or regional studies these data must all be combined into water balance schemes that integrate upward from the smallest homogeneous area of measurement to the aggregate area of interest.

Studies of the changing chemistry of soil and of soil erosion and formation are also sorely needed. Human influences on the landscape have come to be important only within the past few centuries, but today they are a dominant factor in the metabolism of the planet. Very little of the Earth's surface remains free of human alteration, and large areas

receive intensive management. More than 1 percent of the total land area of the Earth outside Antarctica is now given to housing, factories, schools, and transportation, 11 percent is cultivated, and over 30 percent is subject to grazing. Additional large areas of forestlands are subject to periodic harvests.

Managed ecosystems, by their very extent, are significant elements in global change. Their role in hydrologic and biogeochemical cycles and in global metabolism are cited in ensuing chapters of this report. Another critical component is the soil as a substrate for life, although it has received little attention in this context. Soils serve as reservoirs of nutrients and water for the higher plants and the biota that inhabit the soil, they function as reactors and exchange elements in chemical cycling, and they are repositories for enormous quantities of organic materials. In spite of intensive study, we still know little with certainty about the dynamics of soil formation, change, and loss. Changes in global climate will alter soil dynamics; changes in soil, as from accelerated erosion, will alter the global storage of nitrogen and carbon as well as the global hydrologic and heat budgets and thus influence global climate. Human welfare is affected even more directly, since our basic food supply is dependent on the remarkably thin and fragile layer that is sufficiently porous, water retentive, and chemically constituted to serve as soil.

There is a common tendency, particularly in North America where farming is a recent activity, to assess soil quality in terms of topsoil or the depth of the principal, upper zone of humus deposition and mineral leaching. In a virgin soil, this layer contains much of the inherent fertility. It is also the layer that is most subject to accelerated water and wind erosion when tilled. With continued cropping, the nutrient accumulations of the layer are eventually depleted, however, and after that it is useful mainly to support roots and to hold water. That topsoil is not always necessary for agriculture, however, is demonstrated at many sites in Europe and Asia that have been farmed for many hundreds and in some cases thousands of years and that now retain none of the features of the original topsoil. With adequate fertilization, yields at those sites are equal to those attainable anywhere else. When topsoil is lost, other parameters assume importance: soil depth and the characteristics of subsoils that determine water retention, nutrient supply, and rooting. Unfortunately, these properties have not been surveyed and mapped nearly so well as have those of the surface.

Our knowledge of processes requisite for the continued suitability of a soil for agriculture is surprisingly limited. In addition to a better understanding of soil biology, we need better measures of physical and chemical erosion rates (to include leaching of dissolved minerals), rates of downward movement and reformation of secondary minerals, and rates of weathering of the substrate parent materials. We also know little about how these processes may be altered in changed environments--for example, with different amounts of dissolved CO<sub>2</sub> and added burdens of acidic oxides of S and N in rainwater or with changes in agricultural practices.

Nor do we have more than scant knowledge of the present state of the world's soils. The Food and Agriculture Organization (FAO) of the United Nations has worked toward the use of common systems for the classification and mapping of soils, but only general, large-scale maps are available for much of the world. Needed details of chemical and biological activities; accumulations of carbon, nitrogen, and other elements; and profile depths and substrata are generally lacking. We may also need more detailed information on local climates, since the distribution of rainfall and length of season are the main determinants of vegetative production and soil processes.

There is, in short, a need for distributed, global studies of the present condition of the world's major soil types and the rates at which processes of soil formation and destruction are occurring. An IGBP should include studies of the following, to be carried out in concert with the FAO and other international and national agencies:

- o Rates and processes of soil formation, erosion, and soil dynamics in soils that typify the Earth's major agricultural systems, such as chernozem (or black prairie soil) in which most of the world's wheat is produced or alluvial soils in which rice is commonly grown.

- o Processes of soil chemistry, including ion exchange, the fluxes of salts and other materials in and through soils, the balance of organic and inorganic constituents, the effects of soil acids, the production of humus, and significant rates of change in any of these. What is important in soil is not so much its origin or intrinsic nutrient content as its capacity to hold water and nutrients and its texture; in other words, its quality in terms of sustained food production.

- o A worldwide inventory of soils, to include their important physical and chemical properties and factors of topography and slope, which are crucial in determining rates of soil erosion. There have been many soil surveys on a reconnaissance scale; to be most valuable, however, they need to be done in terms of soil characteristics and slope. Much of the cultivable land of the Earth is fragile because it is not sufficiently level.

#### *Observations of Snow and Ice*

A change in the volume of polar ice is an obvious indicator of an increase or decrease in global temperature. Yet at present we have no reliable means to assess changes in the inventory of ice in the Greenland and Antarctic ice sheets. Variations in polar ice volumes should be detectable in sea-level measurements, but these data are noisy and influenced by the thermal expansion that results from global temperature change and by local tectonic movements related to the melting of the last major glacial ice sheet. Ground-based surveys are not definitive. A straightforward technique is through satellite altimetry, although to date no such program is planned or in operation. Support for such a program should be one goal of an IGBP.

The glaciers and small ice caps of the world are important factors in

high mountain and high-latitude environments, and their wastage has contributed about 5 cm to the observed rise in global sea level in the past century. In view of the possible rise in air temperature due to future increases in  $\text{CO}_2$ , an IGBP should support continued glacier monitoring as part of an organized international program.

Seasonal snow cover is a sensitive indicator of climate change; because of its high albedo it also has an important influence on the global radiation budget and therefore on global climate. Snow is critically important to the biosphere in many areas, insulating the soil from winter cold and providing soil moisture at the beginning of the growing season. Snow accumulation, melting, and runoff can, to some extent, be managed to aid agriculture, water supply, and the generation of electrical power. On the other hand, too much snow or too rapid snowmelt can have adverse effects: destructive avalanches, the crushing of structures, problems with transportation, and devastation by flooding. Unfortunately, our present ability to monitor the world's snow cover is very poor. Satellite observation using passive microwave radiation holds considerable potential, but more understanding and comparisons of satellite results with field data are needed.

Sea ice, like snow on land, is a factor in global climate through its effect on planetary albedo. In addition, it influences mass, heat, and energy transfer between the atmosphere and oceans and affects the temperature and salinity structure of the ocean. It creates both an obstacle and an opportunity for economic development at high latitudes; and the seasonal sea-ice zone, especially in the southern ocean, is a place of enormous biological productivity. Sea-ice extent can be mapped by passive microwave sensors carried by satellites, and the ice concentration can be estimated. However, in order to incorporate sea-ice dynamics into atmosphere and ocean models, means will have to be found to make synoptic measurements of sea-ice thickness, the distribution of ice of differing ages, and the extent of surface melting.

## MODELING

It is only through simulations with comprehensive models that we can hope to discern the impact of man's activities on the environment. Thus the development of more comprehensive and reliable models should be a clearly stated goal of an IGBP. Since all the components of the environmental system are linked through the atmosphere, the central part of a global modeling effort must be the development of improved climate and general circulation models. We note that this development is now one of the major objectives of the WCRP. What is particularly needed for an IGBP are more realistic treatments of clouds, atmospheric chemistry, ocean circulation, soil moisture, evapotranspiration, snow and

ice cover, and biospheric interactions (Figure 3.1). Current atmospheric models include interaction among these systems in only a primitive manner. Based on past experience the task of building sufficiently realistic models will be a demanding one that will require several decades of effort. While larger and faster computers will certainly be required, the limiting factor is likely to be gaps in our understanding of interactive processes that take place in the systems we seek to model, such as the complex relations that link soil moisture, rainfall, vegetation, and albedo.

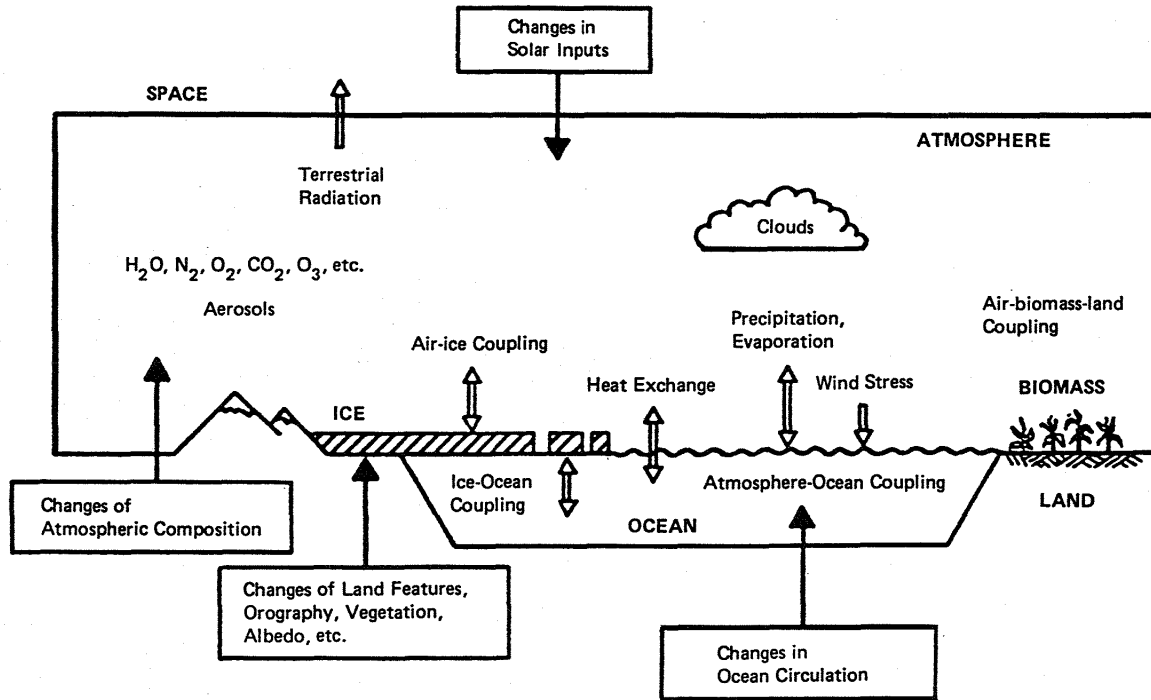
#### *Atmospheric and Hydrologic Models*

A first step in the improvement of current atmospheric general circulation models (GCMs) is to couple them effectively to the ocean and land-surface biomass. To do this their depiction of the surface fluxes of heat, moisture, and momentum must be significantly improved, along with their treatment of cloudiness and radiation. Current GCMs generally do not include interactive atmospheric chemistry or aerosols and do not realistically allow for the interaction of the atmosphere with surface vegetation. The problem of parameterizing local geography in GCMs also needs further attention in connection with regional model validation.

There are many aspects of the global water cycle that are not adequately treated in current models. Three stand out: the simulation of multilayered clouds, of precipitation, and of soil moisture and evapotranspiration in vegetation. In most of the models currently used cloud albedo is prescribed rather than generated by cloud microphysics. The problem is admittedly complex, but since cloud albedo-temperature feedback is potentially one of the strongest factors of the climate system, an improvement is clearly needed. We can hope it will be aided by the acquisition of new empirical data on global cloud cover and vertical structure.

Among the questions involved in modeling precipitation are the following: What are the size distributions of rain drops or ice particles? At what rates do these particles fall or rise? Do solid-to-liquid transitions occur during this transport? How much evaporation takes place as water droplets fall toward the ground? The answers to these questions will require new observations as well as new model design.

Almost all atmospheric GCMs have some means to account for changes in soil moisture. This is important because the evaporation (or transpiration) of soil water has a profound impact on air temperature and circulation over the continents. The schemes in use, however, are rudimentary ones that have been empirically adjusted to produce realistic surface air temperatures. To improve the models will require more



**Figure 3.1** The climate system, involving the atmosphere, ocean, ice, land, and biomass, with some examples of physical processes responsible for climate and climatic change (after Report of U.S. Committee for a Global Atmospheric Research Program, National Research Council, *Understanding Climatic Change: A Program for Action*, National Academy of Sciences, Washington, D.C., 1975).

realistic treatments of such factors as vegetation cover, root depth, soil water capacity, water movement in soils, soil water throughput to the groundwater system, and runoff. Another factor that needs to be included in fully coupled models is the role of atmospheric aerosols, including the production of aerosols by plants, some of which occurs through the process of transpiration from leaf surfaces. Some of the needed information is available from agricultural and forestry research; some has yet to be determined by field observations. The impact of changing climate and of atmospheric CO<sub>2</sub> content on the soil parameters used in these simulations must also be known.

#### *Models of Ocean Circulation*

The ocean transports heat toward the poles and thereby influences regional climate. It also acts as a heat buffer, smoothing short-term climate variations and delaying those of longer term. The ocean is the main sink in the global carbon cycle and hence the ultimate repository for fossil fuel CO<sub>2</sub>. For all these reasons ocean circulation is a fundamental factor in models used for long-term environmental prediction. Yet, many atmospheric models use only passive oceans capable only of simulating their function in buffering heat. If we are to build adequate predictive models we must learn much more about the basic phenomena taking place in the sea. These include wind forcing at the ocean surface, the generation of deep and thermocline waters, and the rates of lateral and vertical transport and mixing within the sea. Although our present knowledge of these phenomena is incomplete, we should strengthen efforts to build GCMs of the ocean while the data needed to define these parameters better are being gathered. The construction of a comprehensive and realistic ocean circulation model is one of the important tasks being undertaken by the WCRP and is the principal justification for the World Ocean Circulation Experiment described above. Indeed, the lack of an accurate atmosphere-ocean GCM now blocks progress in understanding major global changes of the past and stalls our ability to predict the global environmental changes of the future.

#### *Models of Agricultural Carrying Capacity*

Behind many of the scientific questions of an IGBP is the fundamental issue of the human carrying capacity of the Earth, measured in terms of food and fiber production. An obvious, limiting factor is that of soil and soil quality. Since limitations of low soil fertility can be ameliorated through changes in farming systems or through energy-dependent inputs (such as chemical fertilizers), and since human diets are



in principle flexible, there is a wide range of possible estimates of ultimate regional and global carrying capacities. Calculations of carrying capacity made to date view soils as a static rather than a diminishing or accruing resource; nor has adequate attention been given to the influences of changes in the mean or stochastic properties of climate. It is clear that we need to develop greatly improved abilities to assess agricultural potentials, including a range of assumptions regarding climate, technology, and water and resource availability--and that this capability must come from improved models. Increased and continuing attention to their development will help us to distinguish between perceived and real crises in food supply, to identify in advance particularly susceptible regions and circumstances, and to devise possible corrective strategies.

The development of agriculture has enormously amplified mankind's ability to wrest food supplies from the biosphere. Since cropping extracts nutrients from the system, it was limited until recently by the nutrient supplies that were in the soils and by their natural replenishment through weathering, rainfall, flooding, dust deposition, and other processes. The yield levels possible with those sources of replenishment are very low: seed increase rates (the number harvested for each seed planted) before the seventeenth century seldom exceeded 3 or 4 to 1. During earlier eras, gradual increases in the human population were made possible mainly by the expansion of farming onto additional land. Quantum increases in productivity followed discoveries that nutrients, particularly nitrogen, could be refuged from adjacent grazing lands through collection of animal wastes, recycled through animal and human wastes, or enhanced by crop rotation with legumes. As these practices spread through farming systems, they provided the basis for significant increases in the number of people that could be supported per unit area of agricultural land. The principal limitation on improved nutrient replacement and cycling in agriculture is, and always has been, the energy cost measured in human effort or fuel consumption.

The high level of organic farming achieved early in this century in many parts of Europe and Asia through these techniques supported more than  $2 \times 10^9$  humans. By 1930, however, tillage had extended to 11 percent of the ice-free area of the Earth and grazing to over 30 percent, and evidence had accumulated that we were approaching the human-carrying capacity of the globe, based on that agriculture. The remaining lands were much less suited to tillage and grazing, and dietary standards were in decline, even in North America. Further development and extensions of the legume-manure systems, even when supplemented by phosphate fertilizers, promised only moderate increases in food supply.

These older systems made only partial use of the sunlight and water that they received. World grain yields ranged from 800 to 1600 kg ha<sup>-1</sup>, far below the photosynthetic potentials of cereal plants. In simple terms,

cultivated land served more as a place for concentrating scarce resources of nitrogen than as a place for photosynthesis. The advent of abundant fertilizer nitrogen derived from the atmosphere (with the aid of fossil fuels) has changed those rules (Figure 3.2). Crops can now be brought to production rates that are limited mainly by the levels of water, radiation, or  $\text{CO}_2$ . Soil acidification is accelerated by  $\text{NH}_3\text{-N}$  additions, and other nutrients are removed more rapidly as yields increase; but with fertilizer, the role of soil as a source of nutrients is diminished while its importance in supplying water is greatly increased. Agriculture has since kept pace with the rapid expansion in human population, and although regions of malnutrition remain, global dietary standards have improved. A world population of 10 billion people (roughly twice the present number) will require with present methods of agriculture about one third of the cultivable land on the planet--but for sustainable use the tilled fraction must be land that is flat or only moderately sloped. There is nothing on the horizon in chemosynthesis, aquatic sources, or biotechnology that offers a significant alternative to the massive amounts of food that can be produced by higher plants grown on terrestrial sites. Perhaps we can find new and more efficient means of ensuring adequate supplies of nutrients, water, and  $\text{CO}_2$  to crops, but until that happens our attention must remain focused on the adequacy of conventional agriculture.

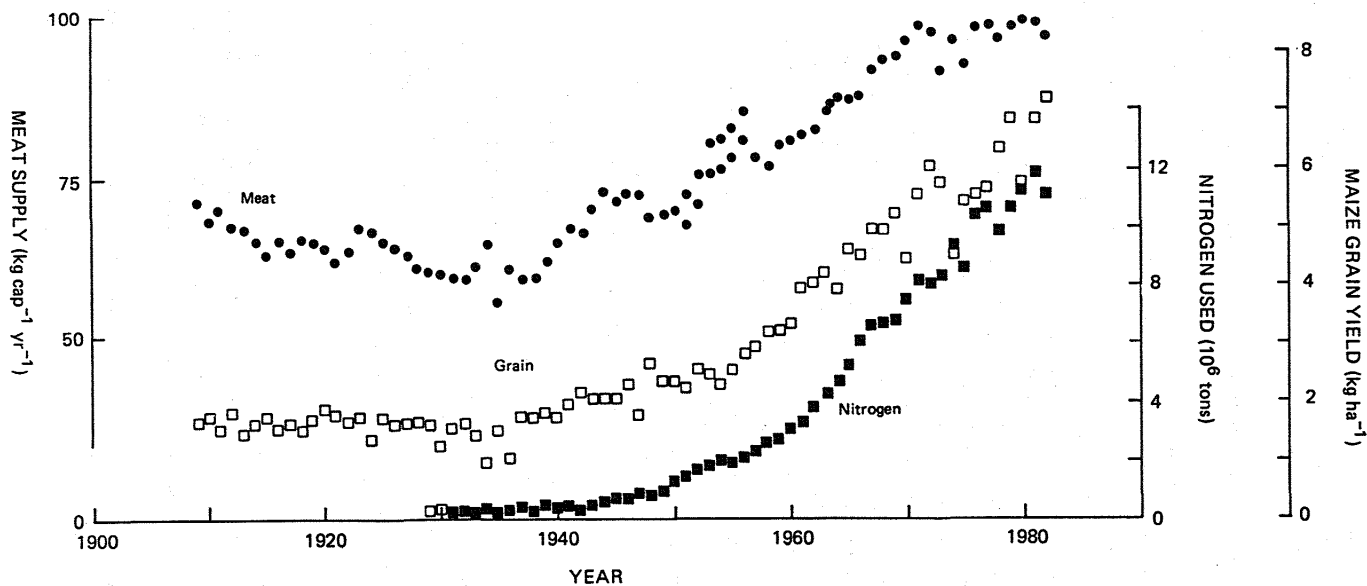
New and serious questions now arise. We are now closer to the practical limits of the photosynthetic productivity of crops. World food supplies are now dependent on energy supplies, and thus on the stability of a larger world society. Among the questions that must be answered, and that can be addressed in part by models, are the following:

- o What is the ultimate carrying capacity of the Earth under different assumptions as to the availability of energy and technology?
- o Are world soil resources being degraded by modern agricultural practices so as to limit present or future sustainable population levels?
- o How do changes in land and water use for cultivation, grazing, or forestry effect evaporation, aerosols, and regional or global climates, and how will world agricultural productivity be affected by changing climate?

#### *Models of Ice, Snow, and Permafrost*

The global heating expected from increases in atmospheric  $\text{CO}_2$  and other greenhouse gases exposes another weak link in our understanding of the workings of the Earth as a system: namely, the interactive role of snow and ice. Among the major questions are the following:

- o How will seasonal snow and sea-ice cover change in the future, and how will this change influence the environment and the climate?



**Figure 3.2** Trends in selected features of United States agriculture and food supply, 1909-1982, demonstrate the marked effects of changes in soil utilization in periods of decades. The retail meat supply per capita year declined steadily from 1909 to 1938 and has since increased dramatically. The U.S. depended on traditional methods of farming during the first third of the century and became a net importer of food in the 1930s. Hybrid maize with improved disease resistance and rapid expansion of the use of the legume alfalfa in grain rotations provided noticeable improvements from 1938 to 1950, but the most dramatic increases in grain yields (and thus meat supply) came with the use of nitrogen fertilizer. Meat supply includes fish (generally less than 10 percent of the total); maize yields are given as an index of feed production; and nitrogen fertilizer is the total applied to all crops. (Source of data: *Agricultural Statistics*, U.S. Dept. Agriculture, Washington, D.C.)

o How will the amount of ice stored in glaciers, ice caps, and the great ice sheets change in the future? What feedbacks on climate will follow, and how will this affect sea level and in turn the coastal environment?

o To what extent will permafrost thaw, and how will this affect the use of northern or high-altitude lands?

The answers to all of these can come only through realistic global models.

Atmospheric GCMs simulate the growth and decline of snow cover, a variable important to the models because of its key role in determining surface albedo. However, existing models are less than precise in predicting precipitation patterns, and only rudimentary relations are used in simulating snow accumulation and melt. Furthermore, topography at subgrid scales is critical to the formation of snow cover in many regions, and this has not been adequately modeled. Considerable improvement is therefore needed before atmospheric GCM's can adequately simulate present-day patterns of snow cover or before they can hope to predict the pattern of future climate. In addition, new developments are required to provide the synoptic, remote sensing of snow that is needed to validate these models.

Sea-ice models that include both thermodynamic and dynamic processes need to be coupled to atmospheric and oceanic GCMs because of the important role that sea ice plays in fixing planetary albedo and heat flux between air and sea. The task of modeling sea-ice formation is complicated by the role of ocean salinity and vertical mixing and by the intimate dependence of sea-ice extent and other characteristics such as the existence of polynias--or areas of open water--on wind speed and wind direction. Although complex sea-ice models exist that include most of the essential physical processes, there are no simple, efficient models of demonstrated validity for use in comprehensive, coupled atmosphere-ocean circulation models. Considerable model development, field studies [such as the International Marginal Ice Zone (MIZEX) program], and improved remote sensing are all required.

Global effects of changes in land-ice cover, particularly on global sea level, needs to be understood better. The present-day rates of change of the major ice sheets (in Antarctica and Greenland) are not known but are thought to be close to zero. Major questions pertain to iceberg discharge from Greenland and Antarctica, melting at the base of ice shelves in Antarctica, and surface melting in the ablation zone of Greenland. The mass balance of the smaller glaciers of the world has been generally negative for the last century, and their wastage has contributed about 0.5 mm/year to sea level rise. In order to predict what will happen to sea level in the next century, greatly improved models will be required. Of special importance is a better knowledge of the processes that might

allow warm, deep ocean water to penetrate onto and under the Antarctic ice shelves, since the thinning or loss of these ice shelves might allow rapid ice stream flow and the loss of ice from land. Along with this, an understanding of iceberg calving and the factors that determine the seaward limit of ice shelves is needed. Better atmospheric circulation models, with attention to parameterization of topography at subgrid scales, will be required to predict the likely wastage of small glaciers and parts of the Greenland ice sheet. An additional problem is that of the prediction of future accumulation in Antarctica; some climate models suggest that snow accumulation will *increase*, taking water out of the oceans.

The warmer temperatures anticipated in polar regions as a result of greenhouse warming will likely cause the permafrost to thaw. Attempts must be made to model the penetration of heat and liquid water through the soil zone into the underlying frozen ground. Long-term melting of these deeper horizons must be considered, not only for the direct effects on soil stability but also because deeper layers of permafrost are thought in some areas to consist in part of methane clathrates, whose melting could release methane to the atmosphere.

#### *Solar and Solar Terrestrial Models*

Two parallel efforts are needed to provide the theoretical basis through which measured changes in solar inputs can be interpreted and eventually predicted in terms of terrestrial effects. As discussed in the previous sections, the first is an improvement in global models of the atmosphere, biosphere, and oceans and their coupling. Such models need to be expanded to include the effects of changes in latitudinal insolation, for example, and the imperfectly understood effects of solar irradiance variations on the upper and middle atmosphere and their coupling to the troposphere. Spaceborne observational programs such as the Upper Atmosphere Research Satellite (UARS) will do much to provide the data needed for these analyses. An ultimate understanding must also include the role of the biosphere and the levers of atmospheric chemistry, dynamics, electricity, and biogeochemical and particle precipitation processes, as probable amplifiers of small changes in solar fluxes at the orbit of the Earth.

A second need is an improved theoretical understanding of the mechanism of solar variability itself. In spite of the presence of a long and well-documented record of the 11-year activity cycle of the Sun, we are still unable to explain its cause, other than through elementary dynamo models that couple solar differential rotation with hypothesized subsurface magnetic configurations. Such models replicate the observed solar cycle only crudely and are as yet wholly unable to give meaningful

information on cycle amplitudes or on long-term secular effects such as the Maunder Minimum that depressed solar activity for 70 years in the late seventeenth and early eighteenth centuries (see Figure 2.4). Predictions of solar activity and of the timing or amplitude of any future 11-year cycle are today done almost entirely by statistical methods whose accuracy is far from adequate for many practical purposes.

#### *Coupled Environmental Models*

A pervading physical element of the environment is the coupling or interaction between the atmosphere, solar inputs, ocean, snow and ice, soil, and biota that determines the course of global change. To portray and possibly to predict these changes adequately, it is essential that realistic models of the entire coupled global system be developed. Not only must atmospheric GCMs be coupled at the air-sea interface with realistic fluxes at the ocean surface, they must also be meshed interactively with appropriate models of the land surface and its vegetative cover and the other factors noted above. Models developed for individual subsystems need to be tested in interactive mode, first from the point of view of identifying obvious incompatibilities and interactive instabilities and then against observation. Steps toward this end have already been taken, but the ultimate goal is a major challenge.

## 4 THE BIOSPHERE

### INTRODUCTION

Almost all known forms of life have evolved in, and are confined to, the Earth's surface and its waters, at or near the interface with the atmosphere. Within this remarkably thin realm reside millions of different organisms, all exhibiting many similarities at the genetic, metabolic, and biochemical levels but each distinctive in how it interacts with the physical and biological environment. At work throughout the history of life on Earth has been a strong interaction between the activity of organisms and the development of soils and sediments, the cycling of constituent elements, the movement of water, and the composition of the atmosphere. Global climate and the chemistry of air and water and soil would all be different from what they are today were there not life.

The nature of this interactive relationship has changed through time as new organisms have come into dominance in response to the continually changing physical and biological environment. The change has not always been gradual; from time to time episodic, cataclysmic events have apparently caused large and rapid environmental perturbations resulting in wholesale extinctions of certain species. In evolutionary time the relationship between the survival of any given organism and the suitability of the changing environment of Earth is a tenuous one.

Man is a very recent player in the evolutionary pageant, and he differs in many ways from his predecessors and contemporaries. He alone has the capacity to comprehend the nature of his relationship with his environment, and with other organisms. He also has the capacity to modify not only his own environment, but that of other organisms as well in a substantial way. Unfortunately, our understanding of the relationships and dependencies of organisms with one another and with their physical environment has not developed as quickly as our capacity to modify them. Anthropogenic changes in the planetary environment are a unique feature in that they may well exceed the limits of natural regulation. There are many indications that human-induced changes are substantive enough to affect the survival of other organisms, both directly and indirectly, and to pose a potential threat to mankind itself.

We are now at a critical juncture in the history of mankind. Because of our sheer numbers and our increasing capacity to manipulate or affect large regions, our impact is now globally pervasive. Fortunately, we are also beginning to develop the tools with which we can view, for the first time, the total global environment. At the same time we have in hand extensive methods to measure and evaluate the interactions and dependencies of organisms with their physical and biological environment on the microscale. We must become more informed of human-induced environmental changes and plan for their eventual impacts. This will require large conceptual and technological advances, particularly in applying biological and ecological information derived from local studies to an understanding of global-scale processes. We must develop the potential to assess the full impact of ongoing environmental modifications as well as to predict the consequences of projected changes. We need to make an inventory of the Earth's resources and to develop an understanding of the important links between the biotic and physical environment. By such methods we can hope to evolve a global strategy for the development and protection of resources that is compatible with the maintenance of the health of the global life-support system.

#### *The Need for a Global Ecology*

Events of the past several decades have provided dramatic examples of our need to develop a global ecology--a way to perceive and predict the biological consequences of global changes in the environment. We need to know the causes and extent of change and its magnitude and potential duration. Further, we need to be able to predict how organisms will respond to these changes either metabolically or genetically, and how these responses may in turn influence the environment.

The first evidence of human-induced changes in the biosphere on a global scale came with the atmospheric testing of nuclear weapons as a result of which the transcontinental transport of mutagenic agents was clearly demonstrated. The use of exotic pesticides on a large scale (e.g., DDT) again demonstrated that no ecosystem--no matter how remote--is isolated from the global dispersion of materials, toxic or benign. Since then, long-distance movement of metabolically active substances in the atmosphere, rivers, and oceans has been demonstrated over and over again. Dramatic recent examples of human-induced changes having a transnational impact are the combustion of fossil fuels contributing to acid rain, air and water pollution, and the increase in atmospheric CO<sub>2</sub>. It is this latter phenomenon, perhaps, which points most emphatically to the need for a global ecological perspective. The increase stems chiefly from the combustion of fossil fuels and a possible shift in the ratio of production to decomposition (including fire) in the Earth's ecosystems



owing to biomass harvesting and land clearing for agriculture and human settlement (Figure 4.1). These changes influence atmospheric CO<sub>2</sub> concentration directly, and in turn affect plant production.

It is now clear that there will be a marked enrichment of CO<sub>2</sub> in the atmosphere that seems destined to alter the world: directly through modification of the global energy balance and indirectly through effects on biota. Yet the interactions among atmospheric and oceanic CO<sub>2</sub> content, climate, anthropogenic sources of nutrients, and the biota are exceedingly complex and only poorly known in quantifiable terms. We do not have sufficient information to make precise predictions of the full impact of CO<sub>2</sub> changes because of uncertainties in the effects on climate, as well as a lack of precise information on the biotic responses to either CO<sub>2</sub> or nutrient enrichment or to climate change. We do know that different species will respond differently to CO<sub>2</sub> enhancement: a fact that complicates simple predictions. Furthermore, CO<sub>2</sub> enrichment may affect decomposition as well as production processes.

At present, there is no objective way to extrapolate point measurements of terrestrial CO<sub>2</sub> fluxes to global scales. For example, most recent assessments of global carbon storage and fluxes depend entirely on disparate data for such factors as net primary productivity, litter production, deforestation, soil erosion, river transport, and marine sedimentation. Such efforts draw upon research performed at different places, with differing objectives and assumptions and with widely varying analytic procedures, quality control, and accuracy. Considerable judgment is needed in formulating consistent regional and global totals and in estimating aggregated uncertainties. The reliability and intercomparability of the results are thus likely to be limited. Furthermore, it is important to understand the dimension of the responses of the global system. Presently used approaches are not capable of considering the mechanistic links that drive these large-scale changes.

Remote-sensing instruments on spacecraft using radiation from visible to microwave wavelengths can now provide objectively averaged, regional data for important parameters such as albedo, temperature, vegetative cover, and plankton biomass over large areas of the Earth. However, remote sensing by itself cannot supply the detail and accuracy essential to understand the complexities of geosphere-biospheric interactions. In situ measurements and large-scale models of biosphere processes are also clearly required.

## A GENERAL APPROACH

*The Heritage*

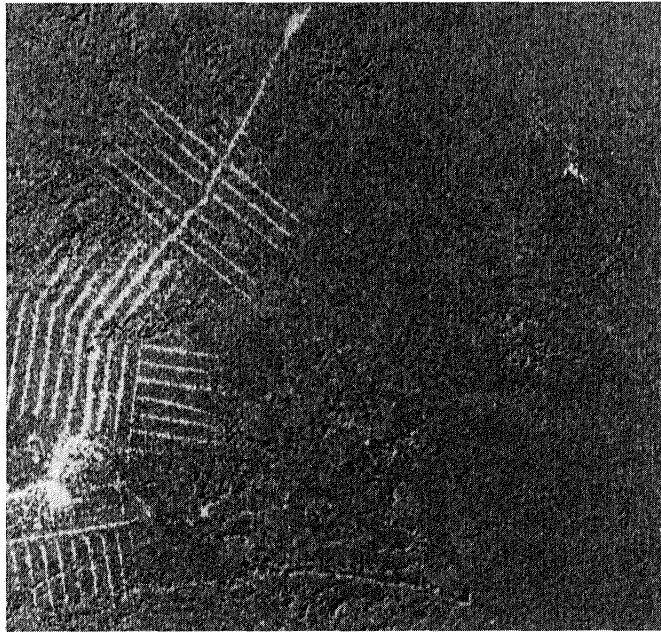
The study of the relationships among terrestrial nonagricultural organisms and their physical-chemical environment is a relatively old science. It has progressed along two more or less parallel pathways: one, examining detailed environmental relations of individual organisms and the other, making correlative observations of the character and distribution of communities of organisms with climate and soils. Only recently have attempts been made to examine the environmental interactions of entire communities or landscape units. These studies were stimulated in part by the International Biological Program (IBP) and in part by the development of watershed approaches to the study of ecosystem function. Such studies provide the basis for estimates of the productivity of the diverse biomes of the Earth.

The close dependence of man on a very few organisms for food has resulted in detailed and extensive studies of crop-environment interactions. The heritage of these studies is a body of information on the productive capacity of crops in diverse climates and under different cultural regimes.

Such investigations have developed from initially descriptive to increasingly predictive ones. Methods utilized for building a predictive capacity have employed a combination of experimentation and modeling. The quantitative models that now exist link rates of certain biological processes with conditions in the physical environment. Models of water transport and utilization exist for individual leaves, whole plants, entire canopies, and complete watersheds, though with decreasing precision at higher levels of organization where experimental verification is more difficult to achieve. Similarly, there are models that predict the intake of carbon dioxide by plants through photosynthesis, for chloroplasts, individual leaves, whole canopies, and even biomes. The accumulation of carbon by primary producers can be predicted reasonably well for crops under a range of climatic conditions, though less accurately for natural plant communities.

Models for the uptake of nitrogen and phosphorus through the soil and into primary producers are now being developed. The turnover rates of minerals between plants and soil are also known at a descriptive level but are to a large extent species specific.

We thus have a fairly good foundation for quantitatively linking the interaction of plants with the movement of carbon from the atmosphere into plants and of nutrients from the soil into plants. We also have information on the interaction of biota with solar and terrestrial radiation as well as with such atmospheric properties as air movement.



We have less capability to predict the movement of carbon and nutrients through animal and microbial components of ecosystems back to the soil or atmosphere.

In sum, we know, and have known for some time, most of the interactive processes linking organisms with their physical environment and how they in turn affect such physical parameters as the soil-atmosphere radiative and thermal balance, the water balance, and the movement of elements within ecosystems. For most of these processes we have a solid capability to interrelate them quantitatively, at least on smaller scales.

Similarly, studies of the physiology of the dominant marine plants (unicellular phytoplankton) have led to a quantitative understanding of response of growth to a suite of environmental variables. Dissolved inorganic carbon is sufficiently abundant in seawater to preclude the possibility that its availability could limit rates of primary production. Rather, it is sunlight and the rate of supply of dissolved inorganic nutrients, mainly N and P, that limit marine photosynthetic production. A substantial portion of the demand for N and P nutrients is met by recycling processes in the upper, sunlit portion of the oceanic water column. Rates of these processes can now be quantified, and these values provide an indirect estimate of the portion of primary production that is

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**FIGURE 4.1** (Top) LANDSAT scene, central Rondonia, Brazil, June 1976. The center of this scene is 10° S, 62° W. The grid pattern is the result of clearing forests along roads cleared by the Brazilian federal government with aid from international development banks. The area is in the southwestern Amazonian Basin close to the Bolivian frontier. Radar imagery from the early 1970s showed clearing only along the main highway and two adjacent roads. (Imagery obtained from the Brazilian Institute of Space Studies, INPE.) (Bottom) LANDSAT scene, central Rondonia, Brazil, May 1981. The area shown is identical to that of (top). A comparison of these two scenes showed that 2200 square kilometers of forest were cleared between 1976 and 1981. The total area of the scene is about 34,200 square kilometers. During the latter half of the period the rate of clearing was twice what it was during the first half of the period. [G. M. Woodwell, R. A. Houghton, T. A. Stone, and A. B. Park (in press). Changes in the area of forests in Rondonia, Amazon Basin, measured by satellite imagery. In *The Global Carbon Cycle: Analysis of the Natural Cycle and the Implications of Anthropogenic Alterations for the Next Century*. J. R. Trabalka and D. E. Reichle, eds., Springer-Verlag, New York.]

exported from the near-surface waters by gravitational settling; they complement direct measurements of particle fluxes made with sediment traps. This sinking process for intact organisms, fragments, and feces constitutes the dominant source of food for deep-sea organisms: the unused residual, when integrated over the water column, results in sedimentary accumulation on the seafloor.

The amounts of C, N, and P that are exported from near-surface waters must be replaced to keep the system in balance. For marine plankton these elements occur in the relatively constant atomic ratio of 106C:16N:1P. The limiting nutrients N and P are replenished by an upward flux from reserves of nitrate and phosphate that exist worldwide in the deep ocean; these reserves in turn are replenished from animal and microbial processing of material that settles from the surface layer. The carbon in this organic matter is part of the same cycle, and a part of the C, N, and P that sinks as organic matter is lost from the cycle as a result of long-term burial in sediments. The processes of sediment burial and gas exchange across the air-sea interface together with biological processes in the ocean both serve to regulate the Earth's atmospheric content of CO<sub>2</sub>.

#### *The Challenge of Scale and Integration*

The production and decomposition of organic matter on the Earth is of course closely linked to climate--it influences, and is influenced by, such climatic elements as temperature, humidity, radiation, and wind. Further, these biotic processes represent significant controlling points in the cycling of mineral elements. Such processes, when viewed at the biospheric level, can be considered to represent the global metabolism. The balance between production and decomposition has a direct influence on the sizes of the nonorganic pools of C, N, P, and S. Changes in the balance of production and decomposition thus signal, for example, potential changes in climate. In recent years, the balance may be shifting owing to major changes in landscape use associated with cultivation, irrigation, deforestation, and desertification. At the same time the factors that control global plant productivity are also changing owing to anthropogenic alterations in the environment. Productivity, for example, may increase with increasing CO<sub>2</sub> but decrease with air and water pollution.

At present we are unable to measure total global metabolism, but we can measure or estimate it for large areas of the ocean and for specific ecosystems or smaller units on the land. Spaceborne sensors now being considered for deployment in the 1990s will make it possible to obtain estimates of certain components of global productivity, but extensive verification by in situ methods will be needed in order to calibrate these results. This effort is important since once the validations are made, we will have the capability of determining the metabolic status of the

Earth's biotic systems both quickly and continuously. The linking of levels of approach--from local to global scale--in the study of biospheric metabolism will constitute an important step forward since it will involve the linking of biological and geophysical models that have been developed in isolation. The important interactions noted earlier between the world's biota and atmospheric and geospheric processes make this linkage a crucial step in understanding the Earth as a system--and our best hope for better global predictive models.

#### *A Specific Approach*

What is needed is an assessment of the Earth's metabolic capacity, which involves studies at overlapping levels of resolution and is fully integrated with geophysical measurements and modeling. There are three specific goals:

- o To quantify our knowledge of production and decomposition processes both regionally and globally and to determine the factors--climate, soils, nutrients, water, and competition by other organisms, for example--that control them.

- o To obtain data on the details of the biological inputs into biogeochemical cycles and microscale and mesoscale climate processes.

- o To account for the diversity and the losses and additions of major biological participants in the global metabolism, as well as the changes in biomass distribution.

In pursuing these objectives it should be noted that important events may take place in very short time intervals, that very limited areas may play a disproportionate role in the global balance, and that not all species are equally important in their contribution to the global metabolism. Special attention should be paid to the interactions of climate, soils, and crops, since it is these relationships that are most crucial in supporting the growing human population.

In addition to studies of global metabolism, which would link directly with coincident studies of the atmosphere and geosphere, we need global inventories to assess the changing balance between species extinctions and invasions and experimental manipulations of entire ecosystems to determine the mechanics of geosphere-biosphere interactions.

#### A PROGRAM

The task of unraveling the complex and detailed interactions that link the Earth's physical-chemical environment and its biota is a monumental one, for which 10 or 20 years is a very short time. It is essential that a comprehensive program such as an IGBP sharply focus on a restricted set of problem areas that would most benefit from a

multidisciplinary approach and that might lead to a new understanding of the central processes maintaining life on Earth.

What follows are three new approaches to the study of biospheric phenomena that promise comprehensive and basic information on biospheric structure and function.

The first represents an effort of measurement and modeling designed to make the essential links between local, regional, and global observations. The second proposes an inventory of the changing nature of the Earth's biota. (This latter effort would not endeavor to account for those factors controlling species interactions, distributions, or metabolism--the main focus of much of biology; instead it would concentrate on building the data base to provide a necessary view of the changing distribution of the Earth's biota.) The third is an experimental program to provide new information on the nature of geosphere interactions at the level of ecosystems.

The general questions posed are the following:

- o What techniques can best be used to refine our estimates of the total exchanges of mass and energy between the geosphere and biota, and what is the best means to monitor these exchanges continuously?

- o What are the impacts of an anthropogenically modified environment on the production and decomposition processes of biotic systems?

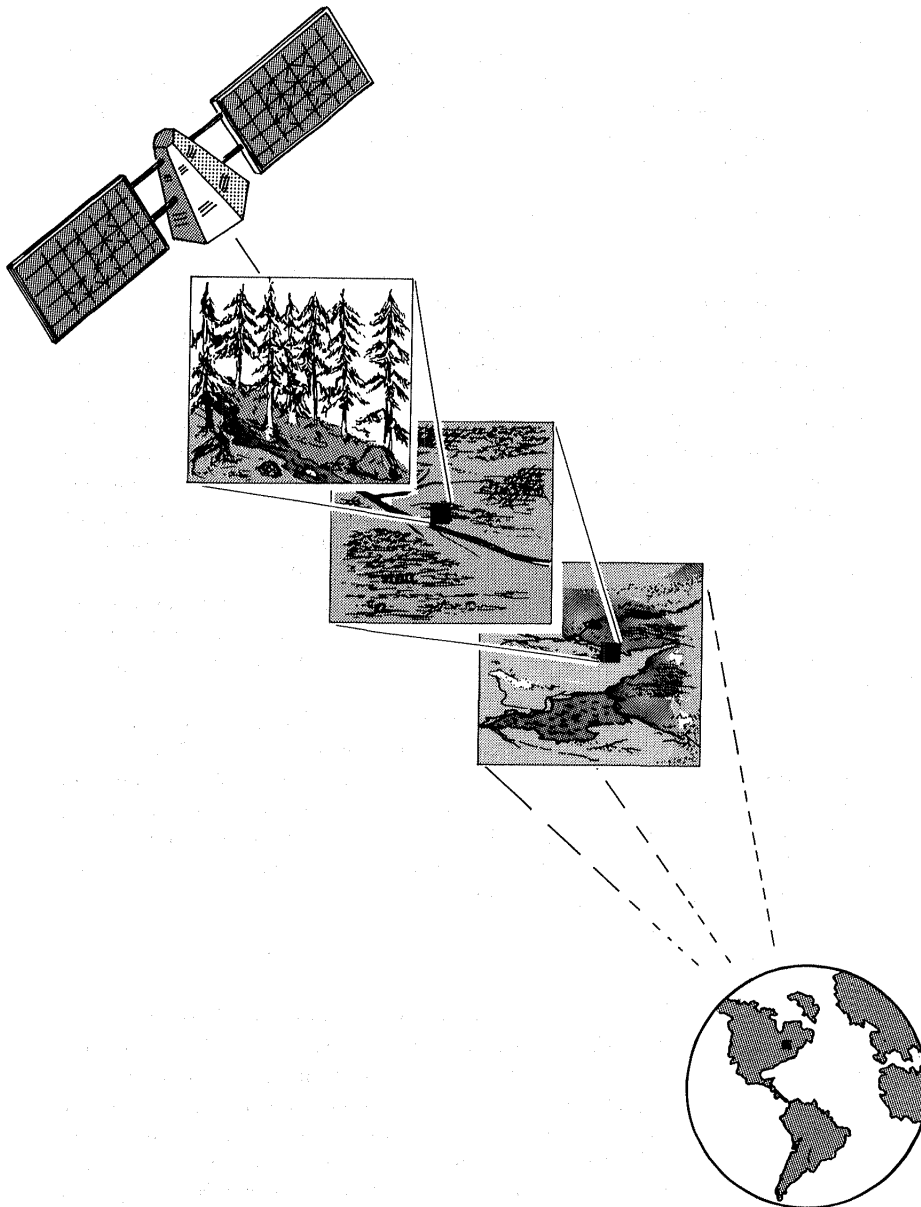
- o How are the Earth's biotic resources restructured by human influences?

#### LINKING LOCAL WITH REGIONAL APPROACHES

A major problem in studies of global ecology is how to relate local or small-scale observations to questions of regional or global scale (Figure 4.2).

##### *A Hierarchy of Levels*

An obvious nesting of units of study would proceed from a global view (utilizing satellite imagery) to regional units (or macrocells, utilizing aircraft and above-canopy climate towers or ships and instrumented buoys) to the level of relatively homogeneous ecosystem units (or microcells, utilizing in situ measurements and experimental techniques). At each level there must be an accounting for interaction between models developed separately for physical and biological realms. Where models do not exist in common scale they would need to be developed. As an example, the atmospheric general circulation models (GCMs) generally utilize a grid size of hundreds of kilometers, at which scale there are no analogous biological models. The development and inclusion of biologically realistic energy balance models at this scale would expand the power of the GCMs and would provide an important input to the



**FIGURE 4.2** Studies of global ecology rest on nested studies at progressively higher resolution, proceeding from a global view to a microcell. Macrocell units, about  $100 \text{ km}^2$  in area (middle), are proposed as possible Biosphere Observatories in an IGBP.



assessment of global metabolism. It would also provide a link to smaller-scale approaches. It will be necessary also to link models of the various scales (global, macro, and micro) within the separate biological or physical realms. In these linkages, measurements at one scale can provide validation for models at other scales.

#### *Satellites and Global Metabolism*

Satellites offer global coverage of Earth surface properties at resolutions extending from hundreds of kilometers to 1 km or less. It is expected that measurements of a number of biological and environmental properties will eventually be made routinely from satellites, including ocean plankton concentration, terrestrial biomass, moisture content, and perhaps even leaf area index and a measure of leaf protein content. Correlations of these variables with spectral reflectance and emittance properties are now being made, although at this stage these studies are exploratory and the identifications are dependent on site or species. Absorbed photosynthetically active radiation and surface temperature can now be measured in both marine and terrestrial systems. These measures can give a low-resolution estimate of the changing productive capacity of the Earth over the course of a year, although plant decomposition, among other things, cannot be accounted for in this manner.

One of the most rewarding activities of an IGBP would be efforts to improve the capability of satellite-based measurements of biological properties. Such efforts would compare spaceborne observations of spectral reflectance with continuous in situ measurements made at replicated, macrocell stations on land and at sea. Only through such a comprehensive validation program can we hope to make more realistic estimates of regional and global metabolism.

#### *Global Circulation Model Cells*

The global climate simulated in GCMs includes wind, temperature, and humidity at the Earth's surface as prognostic variables, together with diagnostic values of cloudiness, precipitation, and radiative flux--each of which is calculated with a horizontal resolution of several hundred kilometers. Such GCMs require the specification or parameterization of the surface fluxes of heat, water vapor, and momentum on the same spatial resolution. Currently used flux parameterizations are based on bulk aerodynamic formulas and are applied uniformly for all land-surface conditions.

A number of problems arise when one attempts to couple these models with local surface vegetation, which is characterized by elements of much smaller scale. One needs a method both for aggregating the fluxes from local surfaces onto the larger scale of climate models and for distributing the model's large-scale meteorological variables onto the

smaller scales of local surface vegetation. Such problems typify the steps needed to achieve an effective, interactive coupling between atmospheric and biomass models.

### *Regional Units*

#### Landscapes

The Earth's topography is complex at all scales, providing a mosaic of habitat types that differ in suitability for different organisms. Adding to this complexity is the fact that any habitat presents an assemblage of organisms whose makeup is a function of the time since the last ecological disturbance. Communities of organisms generally progress through a series of distinct stages. The activities of man have greatly increased the complexity of these landscape units by a variety of manipulations. Accounting for the detailed interactions of these landscape units with the atmosphere and geosphere is obviously a complex task, yet it is essential that we do so in order to assess fully the consequences of the increasing tempo of landscape modification.

It should be possible to view the metabolism of landscape units as a function of time as well as to account for their changing biological complexity. A possible way to accomplish this is to establish a number of local Biosphere Observatories, each of which is a regional research station that defines a landscape unit (or macrocell) covering about 100 km<sup>2</sup> (Figure 4.2). Utilizing instrumented probes extending above the influence of the immediate vegetated cover, it might be possible to measure the atmospheric and radiative properties that characterize the macrocell--although this would require the development of a reliable means to assess the local variations in fluxes of gases such as water vapor, CO<sub>2</sub>, N<sub>2</sub>O, NO<sub>x</sub>, and methane. Such measurements have been made, although they are of low precision and limited by conditions, season, and level of flux. Continuous measurements of gas fluxes at the Biosphere Observatory were they proven possible would be of enormous value in themselves, although considerable development would be needed to establish their applicability to a larger domain. The long-term measurements of CO<sub>2</sub> in Hawaii, for example, demonstrate a marked seasonal change in abundance that gives an index of globally integrated landscape metabolism.

Measurements at such Biosphere Observatories could provide a measure of the metabolism of a landscape unit and furnish the small-scale information necessary to build toward larger cells in modeling efforts. They could serve also as a fixed network of stations for validating satellite measurements of spectral reflectance and other surface properties. Airborne probes and satellite imagery could in turn provide information on the changing configuration of homogeneous units (microcells) within the zone monitored by the Biosphere Observatory.

Microclimate arrays within each microcell could typify climate-ecosystem interactions as well as track the changing composition of the atmosphere. These measures could then be related to direct measures of biological productivity and decomposition.

The methodology for modeling and measuring ecosystem-level processes (such as productivity, water, and nutrient balance) at the microcell level was extensively developed by agrometeorologists, soil scientists, and ecologists working both independently and in the IBP. The present challenge is to integrate results from microcells to derive values for larger landscape units and to develop sufficient resolution in these measurements to account for the changes in system processes that may result from changing climate or atmospheric composition.

### Marine Habitats

Regional studies of the marine habitat are necessary to refine our understanding of certain important biospheric processes. Although perhaps 80 percent of marine primary production occurs seaward of the continental shelf, more than 95 percent of the world's marine fish harvest comes from nearshore regions. Moreover, these coastal waters and estuaries are most heavily affected by human activities. We are today unable to provide a quantitative basis for relationships among the physical, chemical, and biological processes that regulate primary production and fish yield in these important habitats. Lacking, in most cases, is a sufficient base of background data and observations. The natural variability of the system must be documented and understood before we can hope to ascertain the magnitude of anthropogenic effects. The role of coastal regions in sequestering carbon, and how this function has adjusted in response to anthropogenic inputs of nitrogen and phosphorus, are examples of other important unknowns.

In large part, these gaps in our knowledge of interrelated systems stem from a less than adequate match of the scales, both temporal and spatial, at which related natural processes are studied. The decade of the 1970s literally opened our eyes, through global satellite sensors, to the complexity of structure in the world's oceans. Sea-surface temperature and ocean color data from spaceborne sensors afforded a previously unseen view of the complex temporal and spatial variability of major ocean currents like the Gulf Stream, Kuroshio, East Australian, and California Current. No longer can one assume that the biologically important features of such currents can be adequately studied from occasional transects across the currents as was done in the past. Eddy-like features, some persisting for months, are common, and their effect on the distribution of biota and rates of activity for organisms at all trophic levels can be profound.

Dramatic examples of temporal variability can also be seen in satellite imagery of the open ocean. The spring bloom phenomenon is

common to temperate coastal waters. Yet in at least one case, the New England coastal waters, decades of shipboard studies had failed to reveal the extraordinary synchrony of this process over the entire shelf and slope region. In general, the biological response to physical processes in the upper ocean, such as convection and stratification, occur rapidly. With greater use of instrumented buoys and satellite observations, the detailed in situ study of production processes can be conducted with an efficiency never before possible by shipboard studies alone.

Many generalizations have been drawn about the biological homogeneity of major ocean basins. Again, however, satellite observations have revealed physical structure that was previously unknown. Compilations of direct and indirect estimates of the open-ocean production of biota are currently in poor agreement. Data sets from in situ studies are small and will remain so, because of the expanse of these regions and the limitations of shipboard studies and resources. Some of the differences in these estimates could result from poor sampling of episodic events that stimulate production. Global coverage of the oceans is therefore a high-priority goal for the proposed mission of the next generation color scanner, the Ocean Color Imager (OCI).

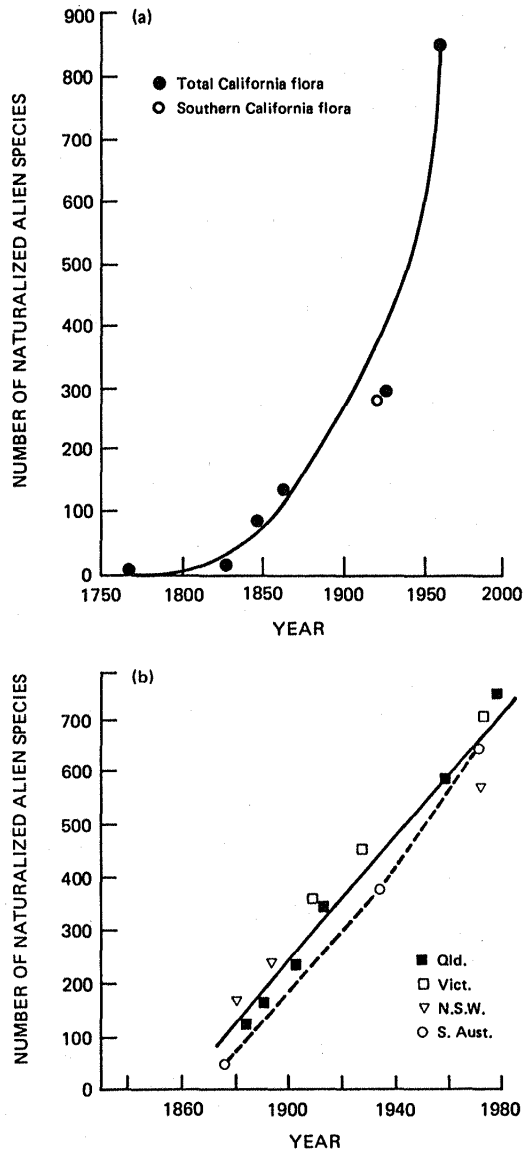
A multiplatform strategy that includes satellite sensors, ships, and buoys will greatly facilitate the study of regional scale phenomena relevant to biological production. A convergence of interests among ocean scientists with biological, chemical, and physical perspectives has led to a determination to take full advantage of a major program involving ocean satellite sensors early in the 1990s.

#### GLOBAL INVENTORIES OF SPECIES DIVERSITY

Evolutionary processes have resulted in the development of complex assemblages of organisms that operate in an interactive manner to capture and process solar energy and mineral resources. These assemblages of plants and animals are in general uniquely adapted to the particular physical and biological regime under which they have evolved. Isolation of the Earth's land masses has promoted this development of biotic diversity.

The activities of man have massively disrupted these natural assemblages through direct destruction of total ecosystems for alternate uses, through selective alteration (as in the case of forestry and range utilization), and even inadvertently by breaking down geographic barriers so that processes of biological invasion are greatly accelerated (Figure 4.3).

We have no global inventory of the magnitude of these biotic disruptions and thus cannot assess their consequences in terms of alterations of ecosystem function. What data we have indicate that two processes are proceeding that are indeed related: the first is an accelerating rate of species extinctions and population reductions; the



**FIGURE 4.3** Rate of increase of alien, higher plants in the last 200 years in California (a) and in four states of Australia (b): Queensland, Victoria, New South Wales, and South Australia. (Compiled by R. H. Groves from various sources.)

second is a dramatic homogenization of the Earth's biota reduction of genetic diversity. As but one example, annual plant species that have coevolved with man in the Mediterranean Basin are becoming weeds with world wide distributions. These invasions are most prevalent in ecosystems that have been disturbed in one way or another by man, but they are also occurring in natural communities. The economic costs of controlling certain invasive species in agricultural areas are enormous. The ecosystem consequences of these invasions and extinctions are largely unknown.

An IGBP would offer the opportunity to gain a world view of the extinction-invasion problem. An initial effort could involve the study of information that is available on the rates of change in species distribution. For example, there are data bases available that give the distribution of endangered species in the United States. A time analysis of this data base would yield an indication of rates of extinction. There are also data available on the rates of spread of a number of particularly invasive organisms. A world survey of invasion characteristics of various taxonomic groups would give the information necessary to improve existing models of the process of establishment, rate of spread, and nature of such invasions. Such an analysis is a necessary first step in assessing the ecosystem impact of these processes with respect to productivity and the movements of water and nutrients.

#### EXPERIMENTAL APPROACHES TO THE STUDY OF ECOSYSTEMS

It is becoming increasingly clear that we lack not only the basic information on how intact natural systems function and interact with their physical-chemical environment but also the basic tools to unravel these relationships.

As one example, it is generally perceived that acid precipitation is a major factor contributing to an observed decline in forest productivity in the eastern United States and parts of Europe. There are, however, a multitude of atmospheric, soil, and biotic factors that affect tree growth. These factors are interactive and are not changing in concert. We can assess how individual factors affect tree growth under controlled conditions in growth chambers. What we cannot duplicate in this way is the complex play of factors that characterize the real environments of natural ecosystems. The difference is both profound and crippling.

What is obviously needed is the design and execution of ecosystem-level experiments under natural conditions to assess environmental interactions. Because of the cost and complexity of such experiments there are not many precedents and few models to point to in evaluating this complex approach. Two that can be cited are the Hubbard Brook study in 1965 of forest control of nutrient cycling in a controlled drainage basin and the chemical manipulation of confined lakes in the Experimental Lakes Area in Western Ontario beginning in 1970, to

demonstrate the impacts of added N and P. Both were enormously revealing in providing information on system processes that could not have been obtained otherwise. Their successes suggest that such studies could afford to be much more daring and more widely applied as, for example, in tests of effects of acid rain or of processes of soil degradation or the chemical manipulation of soils.

Appropriate in an IGBP is the development of a series of experiments at the ecosystem level designed to study the *system* impacts and responses of modified atmospheres, soils, and biomass configurations. These experiments should be conducted on systems for which the need for knowledge is most acute (such as temperate and tropical forests, polar regions, or desert areas) and at sites where the potential interactions between scientific disciplines would be greatest. A possible candidate, appropriate for an IGBP, is the comprehensive tropical basin study suggested in connection with hydrologic studies in Chapter 6. Such experimental initiatives would be most effective if closely allied with programs proposed earlier in this chapter that endeavor to relate local or small-scale processes to areas of larger scale.

## 5 GLOBAL BIOGEOCHEMICAL CYCLES

### INTRODUCTION

The elements carbon, nitrogen, sulfur, and phosphorus are of special interest in the study of life on this planet. With water, they are often the limiting components of living systems, whose growth and decay depend on the supply, exchange, and transformation of these elements. We can begin to understand how the biosphere works by following the transformations that make up the biogeochemical cycles of the individual elements. The need for such investigations has become apparent with growing evidence of anthropogenic perturbations to the chemical, physical, and biological state of the atmosphere, land, and ocean. The magnitude of man-made perturbations is significant; yet we have only a primitive understanding of their causes and ultimate impact.

There is abundant evidence for change at present. Most obvious perhaps are changes in the composition of the atmosphere--of  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{CO}$ ,  $\text{N}_2\text{O}$ ,  $\text{NO}_x$ ,  $\text{SO}_x$ , and  $\text{O}_3$ --and changes in the chemistry of precipitation. There are more subtle effects associated with altering practices of land and energy use and of waste disposal. Anthropogenic changes are superimposed on natural fluctuations, and it is difficult to separate the anthropogenic from the natural changes that are taking place today. There are clues, however, from the record of the past.

An impressive body of information has accumulated recently to suggest that fluctuations in  $\text{CO}_2$  may have played an important role in regulating at least some of the major changes in climate of the past. The level of  $\text{CO}_2$  was approximately 200 ppm during the last Ice Age. It rose by about 50 percent, to approximately its present value, in only a few thousand years, 10,000 to 12,000 years ago, ushering in the present interglacial.

We can reconstruct the history of  $\text{CO}_2$  back to about 60,000 years before present using air trapped in bubbles in ancient ice preserved in Greenland and in Antarctica. A more indirect technique, based on analysis of the isotopic composition of carbon in the carbonate skeletons of marine organisms in ocean sediments, has allowed us to extend the record even further, to about 400,000 years ago. The correlation with



climate is striking. High  $\text{CO}_2$  is invariably associated with warm conditions, low  $\text{CO}_2$  with cold; and indeed, changes in  $\text{CO}_2$  appear to precede changes in climate. This suggests that the geologic record can provide an important means to check and refine models for the present climate and that it can enhance our ability to predict the response of the atmosphere-biosphere system to modern changes in  $\text{CO}_2$ .

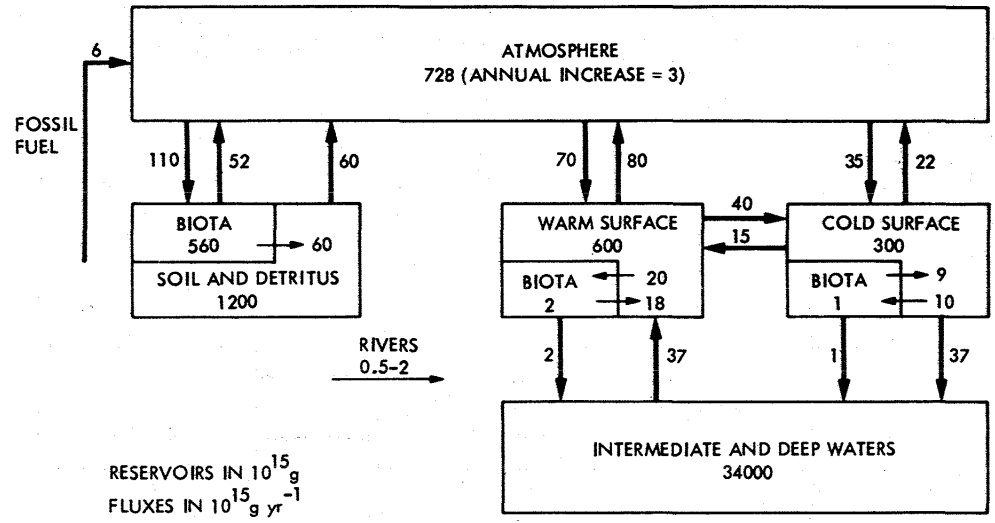
Carbon dioxide is but one of several gases with the potential to raise the temperature of the Earth. Infrared radiation from the planetary surface is absorbed also by methane ( $\text{CH}_4$ ), nitrous oxide ( $\text{N}_2\text{O}$ ), and  $\text{O}_3$  and by the industrial halocarbons,  $\text{CF}_2\text{Cl}_2$  and  $\text{CFCl}_3$ . On a molecule-per-molecule basis, these gases are much more efficient than  $\text{CO}_2$  in altering the radiative balance of the present Earth, and their concentrations are also changing. Their cumulative effect on climate over the past several decades may be comparable with that of  $\text{CO}_2$ . The complex nature and diverse reasons for the changes observed in the composition of the atmosphere require an analysis more comprehensive than any performed to date. Changes in the atmosphere can induce changes in the ocean and biosphere and in the storage and transfer of  $\text{H}_2\text{O}$ , which may in turn affect the functioning of many other parts of the planet.

To illustrate the nature of the scientific challenges that we face, we address here the biogeochemical cycles of C, N, S, and P and the processes affecting several of the important greenhouse gases. This should not be construed, however, to minimize the scientific importance of cycles of a number of other elements--halogens and metals, for example.

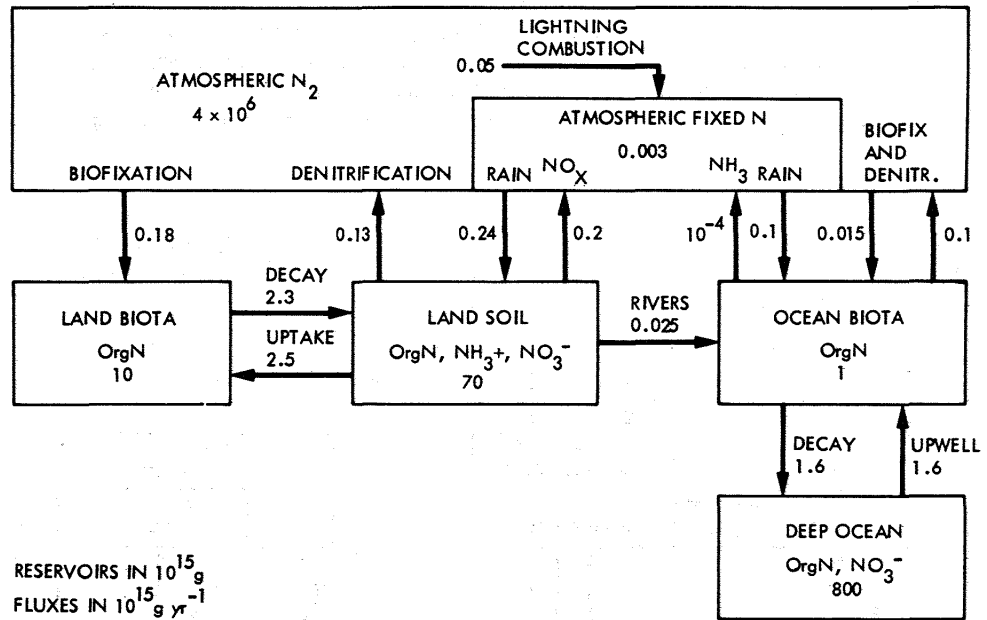
Most of the world's C resides in sediments as calcium carbonate and in organic C. Most of the planet's supply of P is also in the sedimentary reservoir, while N is found for the most part in the atmosphere as  $\text{N}_2$ . Schematic views of the C, N, and P cycles, as currently understood, are presented in Figures 5.1-5.3.

## CARBON

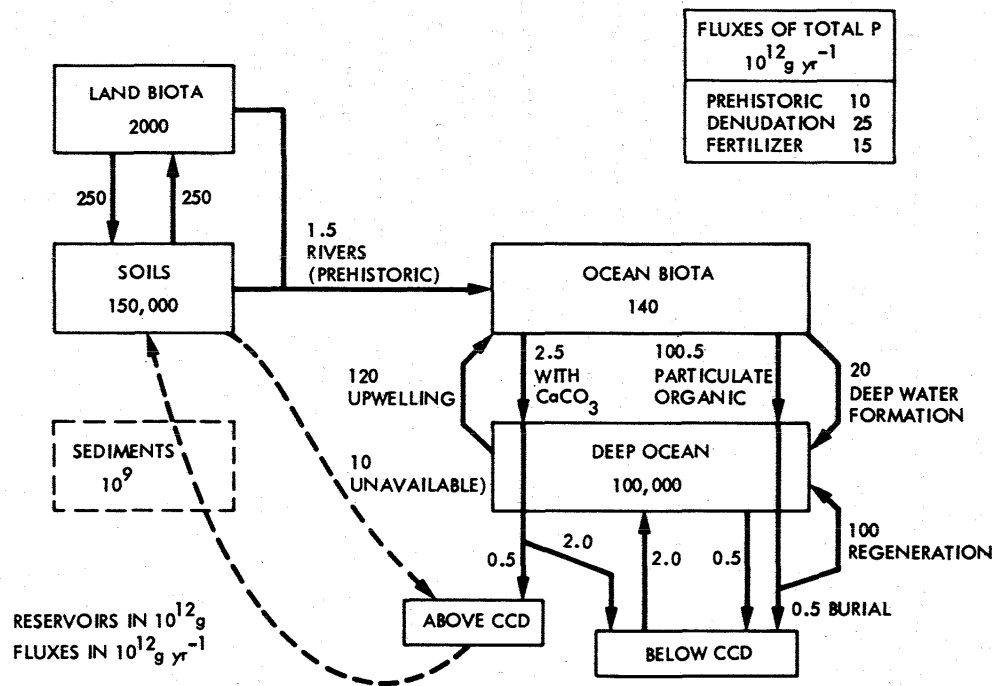
Carbon has a lifetime in the sedimentary reservoir measured in hundreds of millions of years and is released to the atmosphere by volcanic eruptions and by weathering following the uplift of sedimentary rocks. Carbon is then exchanged rapidly, on time scales of tens to hundreds of years, between the atmosphere, biosphere, soils, and the upper ocean, with occasional, more prolonged periods of residence in the deep sea pending ultimate return to the sediments. Carbon, as  $\text{CO}_2$ , is the fuel for photosynthesis. It is returned to the atmosphere from the biosphere and soils by respiration and as a product of microbially mediated decay. The predominant role of  $\text{CO}_2$  in the budget of atmospheric carbon today reflects the pervasive presence of aerobic respiration.



**FIGURE 5.1** The global carbon cycle, showing the present (perturbed) content of major reservoirs and estimated rates of transfer between them. The discrepancies between the outputs and inputs of individual reservoirs reflect present uncertainties in the global carbon budget.



**FIGURE 5.2** The global nitrogen cycle, showing contents of major reservoirs and estimates of fluxes between them. Discrepancies between outputs and inputs of specific reservoirs reflect uncertainties in the global nitrogen budget.



**FIGURE 5.3** The global cycle of chemically available phosphorus, showing contents of major reservoirs and rates of transfer between them. Discrepancies between outputs and inputs of specific reservoirs reflect uncertainties in the global phosphorus budget.

Methane is the second most abundant form of carbon in the atmosphere. Its presence reflects the importance of localized media where oxygen is deficient, as in swamps and the soil of rice paddies, for example, or in the digestive tracts of ruminants and a variety of other animals, including termites.

Carbon dioxide enters the ocean from the atmosphere mainly at middle and high latitudes. It is transformed in the sea from  $\text{CO}_2$  to  $\text{HCO}_3^-$ , with some additional production of  $\text{CO}_3^{2-}$ . It is transferred to the deep sea either in the form of organic detritus or as the structural  $\text{CaCO}_3$  of organisms living in the mixed layer or in inorganic form as a constituent of cold dense waters that sink to depth at high latitudes. The waters that leave the surface at high latitudes are replaced by extensive upwelling of bicarbonate-rich deep waters. Upwelling is most intense near the equator and in the eastern portions of the major ocean basins. The slow turnover of the ocean is controlled by the distribution of ocean currents, heat, and salinity. It is thus ultimately linked to the external climate and may be particularly sensitive to the manner in which moisture is transferred from one ocean to another by the air.

The fall of organisms from surface waters and the subsequent release of constituent carbon at depth has a powerful influence in apportioning carbon between the deep ocean on the one hand and the surface ocean and atmosphere on the other. The process has been called a biological pump. If the pump acts with high efficiency, we expect that the level of atmospheric  $\text{CO}_2$  will be relatively low, and conversely, an inefficient pump will serve to raise the level of  $\text{CO}_2$ . It is obviously important to define the complex physical, chemical, and biological factors that combine to determine the efficiency of the pump. The overall cycle of carbon among the atmosphere, biota, soils, and ocean has an associated residence time of about 100,000 years, with most of this time spent in the deep sea. The cycle involving the atmosphere, biota, soils, and upper ocean is mediated for the most part by biological processes, limited in many cases by the supply of constituents other than C-N, P, and water, for example. The biogeochemical cycles of these elements are thus inextricably connected. A disturbance in the cycle of one element leads almost inevitably to changes in the functioning of all the other major cycles, with complex eventual effects on the biosphere and potential impact on the physical and chemical states of both the atmosphere and the ocean.

## NITROGEN

Nitrogen occurring in compounds as single atoms (fixed nitrogen) is chemically versatile and essential for life, with a range of oxidation states from -3 to +5. Processes that break the N-N bond (nitrogen fixation) are relatively slow, amounting to less than  $0.2 \times 10^{16}$  g of  $\text{N yr}^{-1}$ . Recombination of fixed nitrogen to form  $\text{N}_2$  is also slow, owing largely to

the kinetic stability of inorganic, fixed nitrogen ( $\text{NH}_4^+$ ,  $\text{NO}_2^-$ ,  $\text{NO}_3^-$ ) in solution. The recombination reaction is carried out biologically by bacteria using  $\text{NO}_3^-$  and  $\text{NO}_2^-$  as electron acceptors (denitrification). Denitrification takes place in anoxic, organic-rich locations such as flooded soils and estuarial sediments, bottom waters of some deep ocean basins and trenches and in low-oxygen or anoxic waters at intermediate depths in coastal upwelling regions. Denitrification is essential to the preservation of the present level of atmospheric  $\text{N}_2$ . In the absence of biological processes, the atmospheric nitrogen cycle would be open (Figure 5.2), leading to accumulation of  $\text{NO}_2^-$  and  $\text{NO}_3^-$  in the oceans. It is unclear how the global system acts to establish a balance between fixation and denitrification. Mechanisms directly coupling nitrogen fixation to denitrification have not been identified, and indirect connections are not obvious.

Nitrogen is cycled through the biosphere at rates 10 to 100 times as large as the rate for fixation of  $\text{N}_2$ . Inorganic fixed nitrogen ( $\text{NH}_4^+$ ,  $\text{NO}_2^-$ ,  $\text{NO}_3^-$ ) is assimilated into terrestrial biomass at a rate of about  $3 \times 10^{15}$  g of N  $\text{yr}^{-1}$ , but this influx is balanced by decay of organic material. The rate at which inorganic fixed nitrogen is consumed and recycled by biota in the oceans is roughly  $2 \times 10^{15}$  g of N  $\text{yr}^{-1}$  with a large uncertainty. Internal cycles of mineral and organic nitrogen are essential links in the life-support system of the planet.

We now know that NO plays an important role in the removal of stratospheric  $\text{O}_3$  under natural conditions. It is derived mainly from oxidation of  $\text{N}_2\text{O}$  formed by microbial activity in soils and aquatic systems. Nitrous oxide is a by-product of both oxidation (nitrification) and reduction (denitrification) of fixed nitrogen by microbes, with an additional contribution from combustion.

Nitric oxide is also involved in the chemistry of tropospheric  $\text{O}_3$ . If the concentration of NO is high, above about 70 parts per trillion ( $70 \times 10^{-12}$ ), as it is for example in cities and over large regions of the continents, oxidation of CO and hydrocarbons leads to net production of  $\text{O}_3$  through photodissociation of  $\text{NO}_2$ . Otherwise, removal of CO and hydrocarbons results in consumption of  $\text{O}_3$ . The abundance and spatial distribution of tropospheric  $\text{O}_3$  is linked, therefore, in a rather direct way to the processes that control the levels of atmospheric CO, hydrocarbons, and NO.

The supply and distribution of fixed nitrogen affects thus not only the productivity of the biosphere but also the chemical and radiational environments for life.

## SULFUR

Sulfur, like N, occurs in a wide variety of oxidation states and is an essential element for life. In contrast to N, atmospheric and biological transformations between these various states are relatively rapid and

there is no abundant stable S compound in the atmosphere. Nevertheless, the fluxes of S species into and out of the atmosphere are large--sufficiently large that the removal of the element from the atmosphere in the form of wet and dry deposition of  $\text{SO}_2$  and sulfuric acid is now affecting the pH of North American and European lakes and forest soils. The impact of this process of removal on the health and productivity of forests and the ecology of lakes is now an issue of international concern.

Sulfur enters the atmosphere in two dominant ways. Combustion of fossil fuels add sulfur in the form of  $\text{SO}_2$ . Microorganisms in soils and in the surface waters of the ocean putatively contribute additional amounts in the form of  $(\text{CH}_3)_2\text{S}$ ,  $\text{H}_2\text{S}$ , and other reduced sulfur gases, but the precise amount is unknown and controversial. These reduced gases are oxidized to  $\text{SO}_2$  on time scales of hours to days. Anthropogenic and natural inputs of  $\text{SO}_2$  to the atmosphere are apparently comparable in amount.

The  $\text{SO}_2$  is oxidized to sulfate and in this way removed from the atmosphere on time scales of several days. The sulfur oxidization processes depend on atmospheric levels of the OH radical and thus on the abundances of atmospheric  $\text{O}_3$ ,  $\text{H}_2\text{O}$ , nitrogen oxides, and hydrocarbons.

In the soil and in the ocean photic zone, sulfate is taken up by plants and microorganisms. The sulfur is then recycled to the atmosphere through processes of decay; some accumulates in organic matter in ocean sediments. On geologic time scales, sedimentary sulfur is returned to the ocean-atmosphere system through vulcanism.

## PHOSPHORUS

Atmospheric transfer processes are unimportant for phosphorus, in contrast to the cases for C, N, and S. Key exchanges for P are associated with dissolved and particulate transport in rivers, with weathering processes, and with diagenesis in soils and sediments. Much of the P in rivers is in particulate form and is biologically unavailable. A major question here concerns the fraction of riverborne P that participates in the marine cycle and the time scale for effective transfer to the ocean. There is evidence that biologically available P increases dramatically in the mixing zone between fresh river water and saline ocean waters, at least for some of the world's major rivers. Some or all of this input may come from desorption or dissolution of particulate riverine P, enhancing the effective input to coastal ecosystems and to the ocean as a whole. The added P could also arise from marine biota, and much work remains to be done to resolve this question. Additional uncertainty is associated with the storage of P in estuarine and coastal sediments. This phosphorus may be mobilized during periods of lowered sea level.

Biological uptake by P in the sunlit or photic zone of the ocean is extremely rapid, and surface waters are typically low in mineral

phosphorus, except in upwelling zones where P is relatively plentiful throughout the year. Nitrogen and P are present in the ocean in almost exactly the ratio required by phytoplankton (16:1), and it is therefore difficult to discern whether marine productivity is limited by N or P. There is frequently a small residual of soluble P in upwelled waters, after inorganic N has been exhausted, and hence the role of P is often assumed to be secondary. The minor role of nitrogen fixation in this system is a puzzle. It has been argued that nitrogen fixation may be inhibited at low levels of P. Thus the marine cycles of N and P may be tightly coupled in subtle ways. It is important that we unravel the essential interconnections, since fixation and denitrification can provide possibly rapid sources and sinks for fixed N, with potential impact on C and on the life cycle of major ecosystems.

### CARBON DIOXIDE

Carbon dioxide plays an important role in the radiative budget of the atmosphere, intercepting heat reradiated by the planet's surface. As a greenhouse gas it regulates the transfer of energy within the atmosphere and controls the ultimate release of heat to space. An increase in atmospheric CO<sub>2</sub> may be expected to bring about an increase in the global average surface temperature with a compensating decrease in the temperature of the stratosphere. Changes in the lower atmosphere will almost certainly change the behavior of weather systems and hence the climate, but current models may not be able to predict the eventual impacts on the hydrological cycle, on biota, ocean currents, and on the overall biogeochemical cycling of materials in the near-surface regions of the Earth. An accurate assessment of the impact of CO<sub>2</sub> released by burning fossil fuel or by deforestation requires, therefore, a comprehensive understanding of the atmosphere, biosphere, soil, and ocean as an integrated physical-chemical-biological system. A fundamental overall goal of an IGBP should be to provide the information necessary to advance our understanding of and appreciation for the essential linkages that regulate this system.

Fortunately, there is an excellent, essentially continuous, record for the change in atmospheric CO<sub>2</sub> over the past 25 years. The concentration has risen from about 315 parts per million (ppm) in 1958 to almost 345 ppm today. Much of the rise can be attributed to release of CO<sub>2</sub> from combustion of fossil fuel. There are problems, however, in accounting for details of the observed trend. The rise is less than one might anticipate given the magnitude of the fossil source. The difficulty is compounded in that we might have expected that, over the period of these observations, burning of vegetation would have provided a source of CO<sub>2</sub> perhaps comparable with that from fossil fuel.

Estimates of CO<sub>2</sub> production due to burning are based on data defining the area of land cleared annually for agriculture, mainly in the



tropics, and are quite uncertain. The net source of  $\text{CO}_2$  depends on the abundance of C stored in both the biomass and soils of the area subjected to fire and on the fraction of bound C released to the air. We must account also for a net uptake of  $\text{CO}_2$  in areas recently cleared but subsequently abandoned and allowed to return to forest. There are major gaps in our knowledge of the C content of tropical ecosystems and further uncertainties in our ability to predict the fractional yield of  $\text{CO}_2$  from fire. A significant portion of the C involved in burning vegetation may be converted to charcoal, which is relatively inert and could be stored for long times in soils or in river and estuarine sediments. Careful studies of tropical systems are needed to document conditions before, during, and after fire. We need also improved data on the extent of the land area that is burned annually. Observations from space could play an invaluable role but they must be carefully coordinated with ground-based observations and theoretical analysis if their full potential is to be realized. In this connection, space observations have yet to make a significant impact.

The largest known sink for fossil-fuel-derived  $\text{CO}_2$  is the ocean. Carbon is removed from the atmosphere-upper ocean system by turbulent mixing and downwelling of bicarbonate-rich water in polar regions. As noted earlier, gravitational settling of particulate organic material produced by organisms in the open ocean serves as an additional but not well quantified sink. The calcium carbonate contained in structural material of these organisms is the primary source of mineral carbonate in marine sediments. By these mechanisms the ocean is estimated to take up between  $2 \times 10^{15}$  and  $3 \times 10^{15}$  g of C  $\text{yr}^{-1}$  from the atmosphere, approximately half the rate estimated for release of  $\text{CO}_2$  due to burning of fossil fuels,  $6 \times 10^{15}$  g of C  $\text{yr}^{-1}$ .

Published values for the net transfer of carbon from the biosphere to the atmosphere range from zero to about  $3 \times 10^{15}$  g of C  $\text{yr}^{-1}$ . Combining these values with the value for the fossil fuel source ( $6 \times 10^{15}$  g of C  $\text{yr}^{-1}$ ) and the range of values for ocean uptake [(2-3)  $\times 10^{15}$  g of C  $\text{yr}^{-1}$ ], suggests a range of values between  $3 \times 10^{15}$  g of C  $\text{yr}^{-1}$  (6 + 0-3) and  $7 \times 10^{15}$  g of C  $\text{yr}^{-1}$  (6 + 3-2) for the net release of  $\text{CO}_2$  to the atmosphere. The observed increase in atmospheric  $\text{CO}_2$  leads, however, to a lower value for net  $\text{CO}_2$  release,  $2.5 \times 10^{15}$  g of C  $\text{yr}^{-1}$ , indicating either an additional sink for  $\text{CO}_2$  derived from burning of fossil fuel or an error--or at least an underestimate of the uncertainty in other terms of the atmospheric budget. Largest present uncertainty attaches to the values adopted for the biospheric contribution. As noted in Chapter 2, there is recent evidence for enhanced growth of trees in the past 100 years at temperate latitudes, stimulated perhaps by higher levels of  $\text{CO}_2$ , by enhanced supply of nutrients, by more favorable climatic conditions, or by a combination of all these factors. Also, the soil represents a large reservoir for carbon, but we have little direct information on possible changes in

the C content of soils. There is an urgent need for better data on all the processes noted above, including the role of the ocean, if we are to formulate a credible model for the future evolution of atmospheric CO<sub>2</sub>.

## METHANE

The situation for CH<sub>4</sub> is even less satisfactory. Methane, like CO<sub>2</sub>, has an important effect on the radiative budget of atmosphere. It has a residence time in the atmosphere of about 10 years and is removed ultimately by reaction with the free radical OH. Oxidation of CH<sub>4</sub> in the troposphere leads to production of CO and perhaps O<sub>3</sub>. Oxidation in the stratosphere provides a major source of stratospheric H<sub>2</sub>O. Methane is essentially linked to the chemical cycles controlling the concentration of both stratospheric and tropospheric O<sub>3</sub>. Thus it can influence the transmission of solar-ultraviolet radiation to the Earth's surface as well as the infrared radiative balance of the troposphere. These perturbations can exert important effects on the biosphere and significant related consequences for the cycling of critical chemical elements.

The stratosphere is very dry: the abundance of H<sub>2</sub>O amounts to only a few parts per million of the total air above the tropopause. The factors that determine the level of stratospheric H<sub>2</sub>O are as yet poorly understood. The conventional explanation suggests that air enters the stratosphere mainly at low latitudes where convection is most intense and where the tropopause is highest and coldest. Recent observations indicate, however, that the tropical tropopause is not cold enough, at least on average, to account for the exceptionally low values observed for the concentration of stratospheric H<sub>2</sub>O. Exceedingly vigorous convection in localized regions of the tropics may provide the answer. It has been suggested that cumulus convection over Indonesia, for example, or above the Western Amazon Basin, can penetrate to altitudes as high as 20 km. The tops of associated clouds are extremely cold and offer a potential trap for H<sub>2</sub>O in the lower stratosphere. The abundance of stratospheric H<sub>2</sub>O may be linked therefore in a rather direct way to the climate of particular regions of the tropics. Vertical and horizontal transfer of CH<sub>4</sub> and subsequent oxidation at higher levels of the atmosphere provides a mechanism whereby H<sub>2</sub>O, and subsequently H<sub>2</sub>O, bypass the tropical cold trap. We would expect an increase in CH<sub>4</sub> to lead to an increase in stratospheric H<sub>2</sub>O.

The hydroxyl radical, the sink for CH<sub>4</sub>, is a central player in tropospheric chemistry, yet estimates of its concentration and variability over the globe are very uncertain. If we accept current ideas, atmospheric CH<sub>4</sub> is removed from the atmosphere at a present rate of about  $3.6 \times 10^{14}$  g of C yr<sup>-1</sup>. Approximately  $4 \times 10^{13}$  g of C yr<sup>-1</sup> of CH<sub>4</sub> is accumulating in the atmosphere at the present time, indicating a global source of about  $4 \times 10^{14}$  g of C yr<sup>-1</sup>. This number is relatively well defined ( $\pm 50$  percent), limited mainly by our ability to estimate the mean

concentration of tropospheric OH. The individual contributions to the global source are poorly known however. One can argue that agricultural activities may contribute as much as 50 percent of the total emission of  $\text{CH}_4$ , with an additional 20 percent from fossil fuels and from burning of biomass. It appears that the tropics could account for about one fourth of the global source and for perhaps two thirds of what the undisturbed level would be in the absence of human influence.

Analysis of air trapped in polar ice cores indicate that the concentration of atmospheric methane was constant for many thousands of years prior to about A.D. 1600, and that it began to rise rapidly about 250-400 years ago. Methane appears to have increased by about a factor of 2.2 since the Industrial Revolution. Perhaps half of the rise can be attributed to reductions in OH caused by anthropogenic emissions of CO, but our understanding of source mechanisms is inadequate to allow a more definitive conclusion. Clearly, improved definition of sources, and the factors that influence them, is needed if we are either to account for the past or predict the future course of  $\text{CH}_4$ .

#### NITROUS OXIDE

Nitrous oxide is removed from the atmosphere mainly by photolysis in the stratosphere. The removal rate is calculated to be  $10.5 (\pm 3) \times 10^{12}$  g of  $\text{N yr}^{-1}$ , using observed distributions for  $\text{N}_2\text{O}$  and calculated rate coefficients for photolysis. The rate of increase in the atmosphere is currently  $0.7 \pm 0.1$  ppb  $\text{yr}^{-1}$  ( $3.5 \times 10^{12}$  g of  $\text{N yr}^{-1}$ ), with an indication that growth may have accelerated since 1965. Total emissions for  $\text{N}_2\text{O}$  therefore amount to  $14 \pm 3 \times 10^{12}$  g of  $\text{N yr}^{-1}$ . The magnitude of the annual increase, though small, implies a discrepancy in excess of 30 percent between current sources and sinks, a consequence of the long atmospheric residence time ( $\sim 150$  yr) for  $\text{N}_2\text{O}$ .

Nitrous oxide is an obligatory free intermediate in denitrification. Sequential reduction of the N atom provides a respiratory path for a wide variety of bacteria under anaerobic conditions. Denitrification is most often observed in environments isolated from atmospheric oxygen and supplied with abundant sources of oxidizable organic matter in organic-rich sediments, flooded soils, and closed ocean basins, for example. Such systems were once thought to be the principal sources for atmospheric  $\text{N}_2\text{O}$ , but this idea has proven incorrect. Anaerobic ecosystems contain typically very low concentrations of  $\text{N}_2\text{O}$ , indicating that virtually all the  $\text{N}_2\text{O}$  produced by denitrification is consumed in situ.

Significant quantities of  $\text{N}_2\text{O}$  are produced, however, by a variety of aerobic environments. The most intense emissions are associated with rapid oxidation of organic matter, and it appears that the  $\text{N}_2\text{O}$  is produced mainly as a by-product of primary nitrification. This process, carried out by certain autotrophic bacteria, yields 1-3 molecules of  $\text{N}_2\text{O}$  per 1000 nitrite molecules produced under fully aerobic conditions. The

yield of  $N_2O$  increases dramatically under low-oxygen conditions, rising to 10 percent of the nitrite production rate for partial pressures of  $O_2$  below 0.1 atm. It is interesting to note that nitrifying bacteria also produce  $NO$ , with release rates similar to  $N_2O$ . We expect, therefore, that soils producing large quantities of  $N_2O$  might also form copious amounts of  $NO$ , although direct observations of  $NO$  release are currently scant.

It appears that soils in tropical forests emit  $N_2O$  at rates far in excess of those observed in most other environments. An interesting inverse relationship is observed between fluxes of  $CH_4$  and emissions of  $N_2O$ : sites that are net sinks for atmospheric  $CH_4$  have lower emissions of  $N_2O$ . The latter sites tend to be waterlogged, or nearly so. Microbial production of  $CH_4$  is a strictly anaerobic process, while consumption generally requires oxygen. The anticorrelation noted between  $N_2O$  and  $CH_4$  emissions therefore provide support for the view that  $N_2O$  is produced in forest soils by an oxidative process.

It appears that the anthropogenic processes of agriculture, waste disposal, and combustion account for about one third of current emissions of  $N_2O$ . If the present pattern of emissions persists, the abundance of atmospheric  $N_2O$  should grow slowly to about 400 ppb. However, there is little reason to project that emissions should remain constant in the future. Sources associated with combustion and with intensive agriculture are likely to increase, and we might expect increased fluxes of  $N_2O$  from tropical forests disturbed by exploitation. A doubling of  $N_2O$  within the next century is not out of the realm of possibility. Such a change would significantly reduce the abundance of stratospheric  $O_3$  and would also lead to an increase in average surface temperature. A much improved understanding is needed to predict future emissions of  $N_2O$ , and studies of tropical forests, agricultural soils, and aquatic systems are clearly important to this aim.

## DISCUSSION

Our ability to predict changes in atmospheric  $CO_2$ ,  $CH_4$ , and  $N_2O$  may be even more uncertain than we have portrayed here, for we cannot assume that the existing imbalance of sources and sinks for these compounds will not change in the future. To understand how the  $CO_2$  content of the atmosphere will change, we need accurate predictive models that include processes regulating rates of oceanic deep-water formation, global primary production, and fluxes of organic and inorganic particulate carbon to the deep sea. For  $CH_4$  we need to understand the processes controlling levels of tropospheric  $OH$ --a topic complicated by the fact that  $CH_4$  and other biologically produced hydrocarbons (such as isoprene and terpenes) can serve as either net sources or sinks for  $OH$ , depending on the ambient level of atmospheric  $NO_x$ . This comes about because, as alluded to earlier, when  $NO_x$  is deficient the hydrocarbon

chemistry of the atmosphere leads to the destruction of  $O_3$ ; when it is high, as in polluted urban areas, there is net production of  $O_3$ .

To predict the future course of  $N_2O$  we need a deeper appreciation of the nitrogen cycle. As noted above,  $CO_2$ ,  $CH_4$ , and  $N_2O$  are greenhouse gases with recognized potential influences on climate. At the same time their budgets may be altered in important ways by the very climate changes that they instigate. The existence of feedback processes, both positive and negative, demands more realistic predictive models and new observations of many of the governing processes and fluxes.

Theoretical calculations demonstrate that increases in  $CO_2$ ,  $CH_4$ , and  $N_2O$  in the atmosphere will not only increase the average global temperature by several degrees but also substantially modify global rainfall patterns. Such changes in precipitation will also have a direct impact on the global distribution of the biomass and perhaps the distribution of salinity in the surface ocean. As an important factor in global albedo, biomass regulates the amount of solar energy absorbed by the surface of the Earth. Changes in plant cover and plant moisture can also affect the distribution of cloud cover. It is an open question whether this biologic feedback will accentuate or allay the first order climate effect of increasing  $CO_2$ ,  $CH_4$ , and  $N_2O$ .

It is clear through the known effect of greenhouse gases that the rate of cycling of carbon and other elements through the atmosphere, oceans, and biosphere can perturb the global climate and that climate change, in turn, can lead to significant changes in rates of cycling. It is this interdependence that makes the problem of predicting the impact of human perturbations so complex, and why it is the major challenge for a program like IGBP. There is hope that we can begin now to identify certain cause and effect relationships by coordinated studies in different disciplines, by examining the problem at many different time and space scales, and by obtaining new data from a wide variety of sources. For example:

- o A better understanding of the combined influences of biological cycling and large-scale ocean circulation on the quantity and distribution of various nutrient constituents within the sea will help to quantify the ability of the oceans to take up fossil-fuel  $CO_2$ . Three planned or existing programs can be identified that will help accomplish this objective: The World Ocean Circulation Experiment and the program to study transient tracers in the sea are designed to improve our knowledge of how the ocean is mixed. The Particle Flux program is intended to improve our knowledge of the space and time patterns of production and distribution of organic tissues and associated calcium carbonate and opal within the sea.

- o A careful measurement of the rate of change of biomass on the Earth's surface during the next few decades will help to identify the role of land biota in determining the concentration of  $CO_2$  in the atmosphere.

This might be achieved through (1) observations of surface vegetation by spacecraft to define global plant cover and density; (2) analysis of the changing amplitude of the seasonal modulation in measurements of atmospheric  $\text{CO}_2$ ; (3) measurements of changes in the  $^{13}\text{C}/^{12}\text{C}$  ratio in plants and in the atmosphere; and (4) the careful analysis of tree growth as reflected in tree-ring widths, as cited earlier in Chapter 2. Studies are also required to define and to investigate possible changes in the carbon content of soils.

o A study of the processes involved in the cycling of nitrogen and phosphorus in a variety of ecosystems would clarify the impact of combustion-related sources of nitrogen and the importance of the extensive agricultural applications of nitrogen and phosphorus that characterize modern agriculture.

o A field program to identify and quantify the major sources of  $\text{CH}_4$  and  $\text{N}_2\text{O}$  and their response to environmental factors, plus improved estimates of the rate of buildup of these gases in the global atmosphere will provide essential information needed to predict future changes and to provide understanding of past changes in these chemically and radiatively important gases.

## 6 GLOBAL HYDROLOGIC CYCLE

### INTRODUCTION

The global water cycle is in many respects the most fundamental of the biogeochemical cycles. It strongly influences all the other biogeochemical cycles and also plays a direct role in atmospheric chemistry and global circulation, and hence in the shaping of weather and climate. Much of the heat that drives the atmospheric circulation is derived from phase changes of water. Clouds, ice, snow, and surface moisture have important influences on the Earth's radiation budget. The runoff of water from the continents together with precipitation and evaporation at the ocean surface are important determinants of oceanic salinity and thus of oceanic vertical mixing rates.

The intensity of the hydrologic cycle is demonstrated by the fact that an amount equal to the entire global inventory of tropospheric moisture is exchanged with the ocean and the land surface through precipitation and evaporation every 10 days and that the global inventory of surface freshwater could be drained by rivers in 10 years or by evaporation and transpiration in 5 years. The major reservoirs of the water cycle along with the connecting fluxes are illustrated in Figure 6.1.

### DESCRIPTION OF THE CYCLE

#### *Reservoirs*

The great bulk of water on Earth lies in the oceans. This enormous reservoir is involved in processes of exchange with water on and under the land and in the atmosphere on many different time scales. The transport of heat in the ocean is a major factor in determining continental climate. The physical dynamics of the upper layers of the ocean and the exchange of these layers with the ocean below are important factors in the biogeochemical cycles of carbon and plant nutrients.

Another great repository are the extensive reservoirs found deep beneath the land surface and oceans of the Earth. This underground

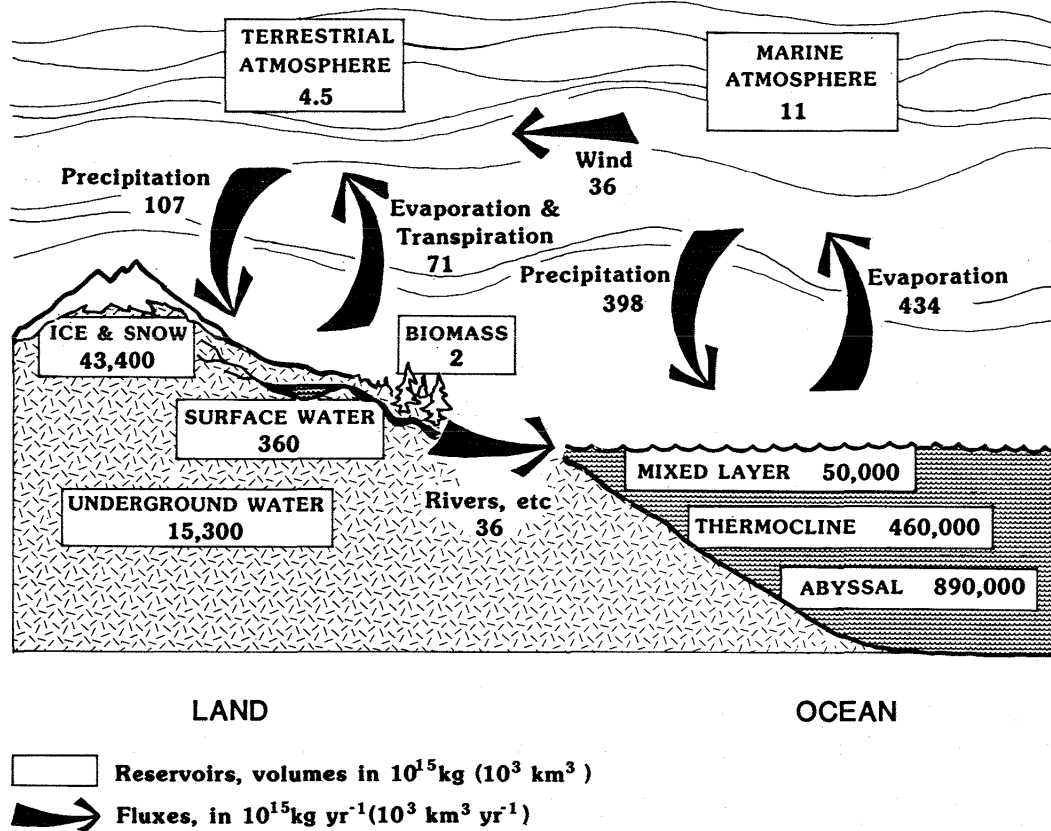


FIGURE 6.1 The global water cycle, showing estimates of contents of major reservoirs and rates of transfer between them. Knowledge of water contained in the ground is particularly poor; this fundamental parameter is known to only a factor of 2 or perhaps 4.



water (or groundwater) stored in porous materials beneath the top meter or so of soil has typical and in some cases as much as  $10^6$  residence times of from 10 to  $10^3$  years. Groundwater is sometimes highly mineralized or contaminated with anthropogenic wastes, including toxic ones. An even larger mass of freshwater exists as ice in the Antarctic and Greenland ice sheets. This ice, with an average residence time of  $10^3$  to  $10^5$  years, participates very slowly in the global cycle. However, it is so large a reservoir that small percentage changes in ice volume can cause major changes in sea level on time scales of  $10^2$  to  $10^4$  years. The addition or subtraction of ice from smaller, mountain glaciers, reacting on time scales of 10 to 100 years, may appreciably affect runoff of certain rivers. The melting of ice in these glaciers appears to have caused a third to a half of the sea-level rise observed in the past century. Snow cover on land and sea ice on the ocean vary rapidly and seasonally and exert a major influence on the Earth's radiation budget and atmospheric and oceanic circulation.

Part of the precipitation on land runs off in streams, and some of the remainder infiltrates into the ground. The topmost meter or so of soil is a chemical and biological reactor, and the water stored there plays an important function in coupling the various biogeochemical cycles. Retained moisture affects the albedo of bare soil and controls the partitioning of net solar radiation at the land-atmosphere interface. Soil moisture, with typical residence times of days to months, provides the potential for moisture fluxes: upward as evaporation and to the roots of plants and downward in recharging groundwater. It serves the same storage and driving functions for dissolved chemical species. Both the carrier and the solutes interact with the soil medium. Soil moisture also plays important roles in soil formation, directly through chemical weathering of rock and indirectly through life support of soil biota. Soil moisture is an active agent as well in the depletion of soil minerals through leaching, and it influences the resistance of soils to erosion. Finally, it also has an obvious and direct effect on the growth of vegetation and hence on global food production.

The volume of water stored as snow can be measured readily, allowing localized forecasts of river runoff, water supply, flooding, and agricultural production. Variations in the areal extent of snow from season to season are greater than that of any other contributor to global albedo changes. Because snow has the highest albedo of any abundant substance on the Earth's surface, its presence or absence drastically alters the amount of absorbed radiation and therefore the surface air temperature.

Just as snow modifies the albedo of the land, sea ice drastically modifies the albedo of the surface of the sea. In the Arctic and sub-Arctic the area of sea ice doubles between summer and winter, from  $7 \times 10^6$  to  $14 \times 10^6$  km<sup>2</sup>. In the unconfined ocean waters of Antarctica the seasonal variation in sea ice extent is much larger—from  $2 \times 10^6$  to

$20 \times 10^6 \text{ km}^2$ . The presence of sea ice modifies the Earth's seasonal temperature cycle, delaying temperature extremes through the release of latent heat by freezing in the autumn and by the absorption of heat through melting in the spring. The growth of sea ice also raises the salinity of the surface ocean waters from which it forms, and locations of extensive sea ice growth are the probable sources of the cold saline water that ultimately forms the bottom water of the world's oceans. The location of the ice edge may also affect the path of cyclonic disturbances in the atmosphere and perhaps the generation of large eddies in the ocean. The seasonal sea-ice zone is also a region of great marine biological productivity.

### *Fluxes*

Solar energy drives the water cycle. Evaporation from the oceans and, to a lesser extent, from the land and its vegetation supplies water vapor to the atmosphere. The atmospheric water vapor is redistributed globally by winds and then condensed and returned to the surface of the land and the ocean as rain or snow. Water reaching the land surface that does not evaporate again is returned to the oceans primarily by rivers but also through subsurface (groundwater) movement and by the calving of icebergs from glaciers and ice shelves.

### *Coupling and Impacts*

Condensation of atmospheric water vapor in clouds and its precipitation as rain or snow are major inputs and driving forces in the hydrologic cycle. The release of latent heat by condensation is one of the strongest forcing factors in global climate. Because of its inherent links with river runoff, soil moisture, snow, and underground storage, precipitation is the critical element for agricultural production and domestic water supply. Floods or droughts, often with catastrophic consequences, can result from an overabundance or marked deficiency of precipitation. Approximately 70 percent of the precipitation falling on the land surface is returned to the atmosphere by evapotranspiration, where it provides a source of subsequent precipitation. Evapotranspiration is vital to plant growth and development and serves as a natural regulator of the surface temperature. It is also a factor in the production of atmospheric aerosols, which are released to the air from leaf surfaces with the evaporation of water.

Storage and depletion of precipitated moisture and the growth of vegetation have characteristic time scales that determine the temporal persistence of hydrologic variations. These dynamic properties are central to modeling the perturbations, trends, and possible instabilities in land-surface biological systems.

The distribution of freshwater is highly variable over the globe and

is poorly correlated with either the density or rate of growth of the human population. Similar inequities arise in the temporal distribution of available water. Rainfall integrated over periods as short as a week is important to the productivity of unirrigated soils. Surface freshwater reservoirs are sensitive to rainfall or snowmelt integrated over time scales of 1 to 10 years; groundwater responds to rainfall integrated over time scales of 10 to  $10^6$  years. An ability to predict and thus to manage better the delivery of water to food crops on the 1- to 100-year time scale would be an invaluable aid to world agriculture.

The temporal and spatial feedback mechanisms that operate between atmosphere and water are important in defining seasonal cycles and the variability of seasonal and interannual components of the hydrologic cycle. During the winter months, the continental land surfaces are net sinks for atmospheric moisture picked up over the oceans; whereas in the summer, when thermal convection is the predominant precipitation mechanism, the depletion of soil moisture by evaporation and transpiration transforms the continents into net sources of water for the atmosphere. Understanding these scales is vital in forecasting the location and size of anomalies in the cycle and in specifying the environmental impact of changes in the land surface.

Some of the problems related to the cycling and availability of water may be considered as local, such as water quality--defined in terms of the content of dissolved and suspended substances. Others transcend national boundaries and may be properly defined as regional or even global problems. These affect, for example, the variability of rainfall on regional and larger scales, changes in gross vegetative type and cover on the land, salinity changes of the oceans, and the long-term availability of freshwater.

#### *Ocean Circulation and the Global Water Budget*

The way in which water is transported through the atmosphere plays a critical role in establishing ocean circulation. A most dramatic example is the contemporary formation of deep water in the North Atlantic Ocean. The best meteorological estimates indicate that evaporation of water from the North Atlantic and its adjacent seas (the Mediterranean, Arctic, and Caribbean) exceeds what is added by precipitation and continental runoff by about 15 percent. The resultant rate of water loss is  $0.3 \times 10^6 \text{ m}^3 \text{ s}^{-1}$  (or 0.3 Sverdrup). This loss of water must of course be balanced by a net return flow of 0.3 Sverdrup through ocean circulation.

There must also be a balance in the salt budget of the North Atlantic. Excess evaporation results in a salinity (and hence density) increase that must be reduced by exchange with less salty water from other oceans. This is thought to occur through a vertical circulation pattern: a shallow, northward flow of less saline waters from the

Antarctic into the North Atlantic and a compensating southward flow of more saline, deep water. The difference in salinity between these two waters is about 0.5 part per mil compared with a mean ocean value of 35 parts per mil. Hence the portion of flow from the Antarctic to the North Atlantic required for salinity balance is  $(35/0.5) \times 0.3$  or about 20 Sverdrups. This predicted flux agrees with that estimated from oceanographic observations.

The mode of operation is thus as follows. As salt increases in the North Atlantic, waters are generated that are dense enough to sink to abyssal depths and flow southward to the Antarctic where a shallow, return flow is generated. The product of deep water flux and salt excess must balance the rate of salt enrichment provoked by excess evaporation in North Atlantic seas. Thus a fundamental ocean circulation is driven by an aspect of the atmospheric moisture budget.

The formation of deep water in the North Atlantic is a process that has wide-reaching consequences. It is responsible for maintaining the benign climate of northern Europe. For every cubic centimeter of deep water formed, about ten calories of heat are released to the atmosphere. This heat input from ocean waters is equal to about 25 percent of the solar energy that impinges on the North Atlantic over the course of a year.

For these reasons it is important to understand how patterns of ocean circulation change with climate. In the process described above it is clear that the rate of formation of deep water in the North Atlantic must respond to changes in evaporation excess, as for example, through variations in insolation or atmospheric circulation. This linkage provides a good example of the strong interdependence of various parts of the environmental system. It also demonstrates how much we have to learn before we can hope to predict climatic changes.

The example is but one of many. We need a better understanding of the factors governing the transport of water in the air and in the oceans. Our knowledge of this aspect of the hydrologic cycle is surprisingly limited, owing largely to the difficulty of obtaining the basic data that are needed. It is almost impossible to determine the net flow of water across geographic boundaries. The net fluxes between land and air and between land and water are also poorly known. Nor are there obvious ways in which any of these measurements might be accomplished.

One approach may offer hope. In atmospheric GCMs the net transport of water across geographic boundaries *can* be determined. By "tagging" the water that enters the atmosphere from any grid square one can follow its subsequent path through the model system to answer questions about, for example, (1) the fraction of local precipitation derived from local evaporation, a measure of hydrologic sensitivity to local landwater change; (2) the regional origin of local precipitation; and (3) the locus of precipitation of locally evaporated water. Moreover such models can be perturbed to determine the response of the hydrologic

cycle to a wide variety of factors and conditions. Since these simulations are inexact and often model-dependent, they do not provide exact answers to real-world problems. They can, however, give valuable clues that can lead to the design of field programs. Observational results can then further adjust the models.

The stable isotopes  $^{18}\text{O}$  and  $^2\text{H}$  should be employed as natural tracers to verify and improve these model studies, as should the historical record of the spread of tritium from nuclear tests. We now have global information regarding the distribution of these isotopes in rain, vapor, and groundwater that should prove valuable in this regard.

#### *Chemical and Biological Considerations*

There are important couplings between the hydrologic cycle and the biogeochemical cycles of C, N, P, S, trace metals, and minor constituent gases of the atmosphere. For example, the runoff of water toward and within streams is an agent for the entrainment, transport, and ultimate deposition of sediments, anthropogenic chemicals, and dissolved and absorbed nutrients. The structure of the stream channel and the biological systems that it supports are significantly influenced by the concentration and the character of these constituents. The eventual concentration of these substances in freshwater lakes and reservoirs is a common cause of ecological change. These changes are exemplified by the effects of acid precipitation on lake environments.

The deleterious effects of man on the quality of water in rivers and lakes and harbors are generally reversible in a relatively short time because of the rapidity with which water cycles through these surface-water systems. However, when toxic materials become incorporated in river or lake sediments it is difficult or virtually impossible to remove them.

Far more serious in the long run may be the injection of toxic or harmful substances into the soil and groundwater reservoirs. Complex chemical and biochemical reactions in the unsaturated soil zone may occur that are difficult to model and predict. Once they have entered the groundwater system, harmful substances may move great distances and remain in the system for centuries to millennia. Because of the complex reactions with soil and rock particles, the long time-constants involved, and our inadequate knowledge of groundwater flow rates and trajectories, this type of pollution is particularly difficult to trace or manage. The unnoted intrusions of today can pose a subtle and serious hazard for the future.

#### PROBLEMS

Our quantitative knowledge of the global water cycle is surprisingly poor. The volume of underground water is not known to within a factor

of 2 or perhaps 4; our knowledge of surface water and of frozen water reserves is somewhat better. Far more serious is our insufficient knowledge of changes in these reserves of liquid and frozen water. We lack understanding of both the rates of change and their causes, as well as the influence of man in provoking these changes.

A major uncertainty concerns the rates of evaporation over land, evaporation and precipitation over oceans, and cloud formation and precipitation processes. Precipitation minus evaporation over land and ocean (or equivalently, the net flow of water from land to oceans and the net advection of moisture from the marine to the terrestrial atmosphere) is not known globally to sufficient precision for understanding and predicting the delivery of water, for example to land-based biota.

Improved understanding of the relation of the hydrologic cycle to the biological, chemical, and geological environment and the development of reliable predictive capability will require answers to a number of important questions: How is the distribution of groundwater over the globe changing both in quantity and composition as a consequence of human activities? What are the spatial and temporal distributions of rainfall, evapotranspiration, and runoff over the Earth, and how do these distributions interact with changes in regional land use and climate? How does the volume of snow and ice on the land and on the sea vary in space and time, and how do these changes influence sea level? What is the net flow of water to the oceans via rivers and aquifers, and how do these affect ocean circulation?

#### PROGRAM GOALS

We propose four general goals for the study of the global hydrologic cycle:

o *To determine the dynamics of the major global reservoirs of freshwater: atmosphere, surface, soil, and underground water; snow, sea, and lake ice; and glacial ice.* This goal recognizes the need to understand the roles of these reservoirs in the hydrologic cycle and their relationship to weather, climate, the global energy budget, and global water supply.

o *To define and understand the mechanisms for the transfers of water between the major global reservoirs.* This goal recognizes the need to understand the processes of evapotranspiration, condensation, precipitation, river flow, glacial flow, melting, and freezing that are responsible for the major fluxes in the hydrologic cycle.

o *To predict on appropriate time scales, changes in distributions, volumes, chemical composition and fluxes of water resulting from climatic change and from human activities in (a) the atmosphere; (b) land-surface, soil, and underground water reservoirs; (c) snow cover; (d) sea ice; and (e) glacial ice.* The relevant time scales are days for atmospheric water, weeks for land-surface water and snow, weeks to years for soil moisture

and sea ice, and years to millennia for underground water and glaciers. This goal recognizes the societal importance of the water cycle and the need to predict changes in important reservoirs and interreservoir fluxes.

o *To understand better the coupling and reactions involving water in biogeochemical cycles.* This goal recognizes the pivotal and complex role of water in man's environment, with opportunities to improve water quality and to optimize food production.

## SOME PROGRAM ELEMENTS

### *Observations*

Observations related to the hydrologic cycle have traditionally been made using networks of stations on the land surface. These networks and their instruments are highly developed in Europe, North America, and other industrialized regions where some records exist that span more than a century. Elsewhere in the world observing networks are sparse or absent, and the records are of a few tens of years at best. More complete global coverage is needed, but there is no current technology for measuring many of the quantities from space. It will therefore be necessary to expand the global networks of on-site station measurements of

- o Precipitation quantity and burden of dissolved and suspended substances (or "quality"),
- o Streamflow quantity and quality,
- o Sediment transport by streams,
- o Groundwater quantity and quality,
- o Atmospheric humidity, and
- o Soil moisture.

In conjunction with this expanded observing effort it is essential to provide centralized data retrieval and archiving to make the data available to the user community.

Since rainstorms are a critical factor in the dynamics of the hydrologic cycle, it is necessary to observe their spatial extent. It is now, or soon will be, possible to do this from space using microwave radiation. Ground-based radar can also be used. Here, as with station observations of storm intensity and duration, it is the statistics of a region's precipitation climatology that are important and not the recording of every storm event on Earth.

A number of important hydrologic quantities can be observed from space, however, and an IGBP should pursue them vigorously. These include

- o *The mass balances of the Antarctic and Greenland ice sheets are*

still unknown in spite of an extensive field effort since the International Geophysical Year (1957-1958). It may soon prove possible to determine these fundamental quantities by repeated altitude surveys, using laser or radar altimeters on polar-orbiting spacecraft. The measurement should be pursued as part of an IGBP because of the role of these reservoirs in climate and in determining global sea level.

o *Glaciers and Small Ice Caps*: The wastage of these secondary ice reservoirs, especially those in the mountains bordering the Gulf of Alaska, in Central Asia, and in southern South America, has contributed significantly to the contemporary rise in sea level. The contribution is likely to increase, given the probability of warmer surface temperatures through global greenhouse gas enhancement. Yet little is known about the current mass balance of glaciers in many parts of the world. Spaceborne methods to measure and monitor volume changes have not been developed, and research on such techniques should be encouraged. In the meantime existing methods of aerial photography and measurements made on the glacier surface should be extended and intensified.

o *Snow and Sea Ice*: The remoteness and scale of snow and sea ice make real-time, global-scale data acquisition practical only with satelliteborne sensors. Over 50 percent of the land is covered and uncovered by snow each year, and sea ice covers about 10 percent of the world's oceans.

o *The Secular Change in Sea Level*: In many areas the sea level varies seasonally and interannually with changes in the heat content of the upper layers and in the velocity and location of ocean currents. These short-period changes may ultimately be best measured from radar altimeters on satellites such as the NASA Ocean Topography Experiment (TOPEX), but the altimeters will need calibration from a network of tide gauges on open coasts and islands.

Long-term changes in sea level can also be expected to follow the climatic changes now anticipated from rising concentrations of CO<sub>2</sub> and other greenhouse gases. A worldwide network of individual tide gauges would probably be the best method for measuring this secular change. A network of measurements of salinity and temperature in the upper 1000-2000 meters of the oceans will also be necessary to separate changes in ocean volume due to thermal expansion from changes in total ocean water mass resulting from glacial melting. Measurements of secular changes in the position of the Earth's pole of rotation and in the speed of rotation would also be useful in making this separation. Possible secular changes in the elevation of individual tide gauges with respect to the center of the Earth must also be determined; this can now be done to an accuracy of about 1 cm by measurements of the acceleration of gravity at the location of the gauge and by satellite geodesy using lasers ranging and radio interferometry.

o *Precipitation and Evaporation over the Ocean*: At present there are



no suitable means for measuring precipitation and evaporation over the ocean, even though an understanding of these processes is essential for interpreting the role of the ocean in climatic change and for a complete picture of the hydrologic cycle. One promising means of point observation of precipitation is by acoustic measurements, made from submerged hydrophones, of the noise made by raindrops falling on the sea surface. Both the size of the drops and their frequency can be determined from the level and spectrum of the acoustic signal. Auxiliary shipborne radar observations are needed in conjunction with this technique to define the spatial extent of oceanic storms.

No satellite-based measurements of evaporation rate are currently in sight, and estimates will continue to be made using the traditional bulk aerodynamic formulae. Controlled experiments are needed to evaluate the diffusion coefficients for water vapor in the presence of breaking waves and consequent aerosol formation.

o *Tropospheric Moisture*: Estimates of the vertical profile of water vapor in the troposphere can be made from space and should be encouraged and exploited.

### *Modeling*

Major efforts should be made to develop conceptual models to better understand why changes are taking place in the hydrologic cycle and to integrate these models with global-scale atmospheric and oceanic GCMs for studies of climate change. Analytical work is needed to develop hydrologic models that successfully simulate such factors as streamflow. Such models should make it possible to predict the hydrologic consequences of postulated environmental changes, such as the higher surface temperatures and altered circulation and precipitation patterns now anticipated in a CO<sub>2</sub>-enriched atmosphere.

### *A Comprehensive Experiment*

An integrated observational program, such as those suggested in Chapter 4 as "ecosystem experiments," might meet many common goals of an IGBP and be of particular value to local studies of the hydrologic cycle. Such a program might undertake an integrated study of a tropical basin such as the Amazon basin. This would involve study of the cycling of water, chemical species, aerosols, and other constituents between surface water, soil, groundwater, sediment, atmosphere, ocean, and biomass. Circulation would be explored at scales ranging from microcells to regional scale, with emphasis at the mesoscale. The program would involve data collection at each of these scales as well as intensive process studies and modeling. The results would be applicable to an understanding of the global carbon and other biogeochemical cycles; prediction of climate change in the future due to anthropogenic release of CO<sub>2</sub>; the role of tropical rainforests in the global hydrologic, atmospheric, and oceanographic circulation; and the effect of man's actions--especially deforestation--on the global environment.

## 7 ELEMENTS OF A PROGRAM

### SUMMARY

We have outlined in preceding chapters some of the factors that lead us to endorse the concept of a focused, international geosphere-biosphere program, whose goal is to understand the interactive physical, chemical, and biological processes that regulate the Earth's unique environment for life, the changes that are occurring in this system, and the manner in which they are influenced by human actions. There is a pressing need to assess the consequence of human activities in the context of natural global change and to provide the body of knowledge necessary to chart a wise course to the future. We believe that the state of our science is ready now to accept this demanding challenge and that the task is sufficiently urgent and of such a scale as to require international and multidisciplinary attention.

Mankind has developed the capacity to influence the environment of the Earth on a global scale--a situation unparalleled in the history of the planet. Our presence is detectable in the remotest regions of the globe in the form of significant changes in the chemical composition of the atmosphere. We have altered not only the air but the soils and albedo of the Earth, the surface and subsurface waters, and the working of the hydrologic cycle itself. On every continent we have so perturbed the natural distribution of plant and animal species that today the world is characterized by an accelerating rate of species extinctions and a dramatic homogenization of biota. No corner of the Earth is free of human influence. More than 30 percent of the land is under tillage, active grazing, and managed forest. Chemicals unknown in nature are being introduced in the air and water and soil in ever-growing quantities. It is we who now fix (and greatly accelerate) the pace of many of the processes that cycle chemical elements essential to life. Yet we know only vaguely the results of these sometimes massive perturbations, or indeed the background of natural process in which they work. In this context the earth and biological sciences have not yet been able to answer the modern, practical questions most often asked of them--in part because we lack a holistic understanding of the Earth and its biota as an interrelated system.

Our present understanding of the Earth has come in discrete pieces from an agglomeration of loosely connected disciplines, such as meteorology and aeronomy, solar-terrestrial physics, ecology, oceanography, hydrology, seismology, and geochemistry. The hope of a geosphere-biosphere program rests on the established prowess and modern capabilities of these and other fields, but its objectives require something more--a synthesis of specializations, directed to provide a deeper understanding of the natural world, to improve the general condition of mankind. The problems outlined in this report are unquestionably of an interdisciplinary essence, with the biosphere as the common link. As an example, we cite the burning of fossil fuel that releases  $\text{CO}_2$  to the air, in such increasing amounts in the present era as to evoke global concern. It is generally conceded that the increase in  $\text{CO}_2$  abundance in the atmosphere will eventually lead to a significant increase in the globally averaged temperature of the surface of the Earth. But knowledge of a modeled, climatic trend is of limited use. To foresee the practical impacts in quantitative terms we need to define the response of the Earth's biota to increasing  $\text{CO}_2$ , as well as that of the soil, the hydrologic cycle, and the ocean, to trace the complex feedbacks that are involved and to determine the ultimate response of the composite system. The need is to predict the regional impacts of change, not simply its global average, and the ultimate impacts of local or regional changes in climate. This task is obviously demanding, and it requires a new step forward, not only in the disciplinary but also in the interdisciplinary dimensions of our science.

#### GENERAL PROGRAM ELEMENTS

A number of specific objectives have been developed in the preceding chapters. They have in common the need for new programs of *observation* of the Earth as a planet, a better understanding of the interactive *processes* that govern its changes, the development of a new generation of coupled *models*, and the design of suitable *tests* to guide the development of these models and the understanding of the processes involved.

We summarize below the general recommendations in each of these four categories, condensed from the more specific recommendations given in earlier sections. We emphasize that the list is neither complete nor all inclusive but rather an indication of the sorts of efforts that must be undertaken to meet the goal of a focused IGBP. Moreover, a number of the programs mentioned are already planned or under way, as features of other international, research programs.

## OBSERVATIONS

Observations of the present and evolving state of the Earth are essential to the aspirations of an IGBP. They provide the input for models. They play a central role in raising questions, stimulating hypotheses, and identifying needs for specific process-related studies. They can substitute, at least on a temporary basis, for gaps in understanding, allowing phenomena not well understood to be represented in an empirical fashion in models. Particularly needed are the following:

- o Continuing, long-term observations of parameters that may provide composite indications of change in global climate. These include sea level, volume of land and sea ice, surface temperatures, clouds, regional and global albedos, and the vertical structure of the atmosphere and oceans. The initiation and maintenance of long-term time series of fundamental measurements are an obvious requirement of any program that endeavors to document and understand global changes. They may well form the principal bequest of an IGBP for future generations of scientists, for questions that we cannot anticipate and problems that we cannot foretell.

- o New observational programs that trace the movement of water within terrestrial ecosystems, the ocean basins, and between sea and land, since these flows are critical to the function of ecosystems and fundamental to the state of the climate. There is also a need to determine rates for evaporation and precipitation and to determine the moisture content of soils. Current observations must be extended to provide better coverage of remote environments.

- o Programs that study the world's current soil resources including key factors of slope, roughness and soil thickness, the physical and chemical properties of soils, and the relative balance or imbalance between soil formation and erosion in representative areas of the world.

- o Observations to define the extent and to monitor change in the distribution of selected, representative ecosystems--tropical forests, for example.

- o A continuing record of extinctions of native species and the colonization of intrusive varieties of plants and animals in sensitive ecosystems. These processes are accelerated by human activities and they may alter the geosphere-biosphere interactions of entire ecosystems.

- o Data to define quantities of important chemical elements--carbon, nitrogen, and phosphorus, for example--stored in major ecosystems. A sampling strategy must be devised to provide early detection of possibly significant changes in the holding capacity of these environments.

- o Continuing measurements of basic ocean variables such as current, temperature, and salinity over the entire globe.

o Extensive observations of the ocean to define rates at which materials are distributed from place to place and from depth to depth. Satellite studies of physical and biological properties together with in situ measurements of chemical tracers, both natural and anthropogenic, can make an important contribution to this objective.

o Continuing measurements of the composition of the atmosphere at a number of geographically dispersed stations to identify changes in the abundance and altitude profiles of specific gases and to aid in diagnosis of factors responsible for the observed changes. Gases that should be included in this program include  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{CO}$ ,  $\text{N}_2\text{O}$ ,  $\text{NO}_x$ ,  $\text{SO}_x$ , and  $\text{O}_3$ . Observations defining the changing chemistry of precipitation are also needed.

o Continuing observations of  $\text{O}_3$  and other selected gases in the troposphere and stratosphere to distinguish changes due to human activity and natural variability.

### PROCESS STUDIES

Resolution of many of the most critical uncertainties in our knowledge of geosphere-biosphere interactions will require experimental studies in both the field and the laboratory. Testable hypotheses now exist for some of these processes; new global observations will be required to design studies to investigate others, and the studies necessary to understand some will be guided by new models that appropriately address geosphere-biosphere interactions. In some cases this will involve an elaboration of existing or planned programs, while in others it will require a new synthesis of ideas and strategies. In an IGBP the emphasis of process studies should be both global and interdisciplinary. Many topics for these studies are proposed in the preceding chapters; summarized below are examples that demonstrate the need for an international program. Particularly needed are studies of

o Processes controlling concentrations of  $\text{CH}_4$ ,  $\text{OH}$ ,  $\text{NO}_x$ , and other important trace gases in the troposphere and stratosphere, to understand the role of these substances in global chemistry and climate. We need to identify and quantify the major sources and sinks of gases whose concentrations are known to vary and to determine the environmental factors that are important in regulating release rates from specific habitats, such as tropical forests, peatlands, permafrost regions, and the oceans. Laboratory studies of some of the organisms involved will also be essential.

o Variations in solar inputs to the atmosphere, such as the total irradiance and those inputs that influence the concentration of stratospheric and tropospheric oxidants, to identify and delimit the role of solar variability as a perturber of climate and of other significant global change. An interplay of models and relevant observations is here particularly needed.

o The processes responsible for the formation of deep ocean water, to understand the fundamental circulation of the ocean and the basic interactions between ocean and atmosphere that influence climate. We need to know the factors that determine the geographic extent of these regions and the magnitude and frequency of downwelling events. It now appears that both physical and biological process in regions where deep water is formed play an important role in the carbon and nutrient cycles of the sea.

o Whole ecosystems--both natural and man-made--to illuminate the real impacts of environmental perturbations. Such studies would employ controlled experiments in regions of perhaps 1000 to 10,000 acres. Good examples are the studies performed in recent years in Canada in the Experimental Lakes Area of Western Ontario.

o The effects of variations in  $\text{CO}_2$ , nutrients, and other environmental conditions on selected ecosystems--such as the effects of industrial effluents or of increased carbon dioxide on tree growth--to specify how these changes influence biological processes and the cycling of water and chemical elements through biosphere-geosphere systems.

o The rôle of physical processes in the ocean and their influence on the production and burial of organic carbon in the sea, to quantify important components of the global cycles of C, N, and P. These will require intensive investigations of representative regions of the ocean. They are essential if we are to make optimal use of the potential of space measurements of ocean color to estimate ocean biomass and production.

o Processes of soil formation and degradation, the salinization and chemical balance of soils and of soil erosion, to understand the impacts of modern agriculture on the global soil resource and to specify the ultimate agricultural carrying capacity of the Earth.

o Specific aspects of the hydrological cycle--for example, the exchange of water between the troposphere and stratosphere, the investigation of dynamical and radiative feedbacks involving clouds, or studies of exchange of waters between soils and the atmosphere. Relevant processes are complex and must be understood better if they are to be incorporated reliably in models.

## MODELS

A major challenge for an IGBP is to develop an integrated view of the Earth as an interactive physical, chemical, and biological system. This is required if we are to provide a comprehensive assessment of the complete effects of modern technology on the global environment. We need to forecast, for example, the changes in climate and weather patterns induced by release of  $\text{CO}_2$  from the combustion of fossil fuel. To do this successfully presumes an ability to predict changes in atmospheric circulation, associated changes in the biota, global snow and ice cover, and the ocean, recognizing that the eventual impact involves a

variety of subtle, complex, and poorly understood feedbacks. To address these issues we need a better understanding of a variety of processes, as noted above, and improved observations. We also need improved models for

- o The circulation of the atmosphere, with better means to describe the radiative feedback of clouds and improved definition of processes controlling exchange of heat momentum, H<sub>2</sub>O, and other chemicals at the surface. Radiative-dynamical-chemical feedbacks with the stratosphere are fundamental parts of such improved models.

- o The circulation of the ocean, both surface and deep water, including definition and quantitative description of mechanisms responsible for upwelling and downwelling. We need an ability to describe the response of the ocean to externally imposed conditions at the surface and also models to describe the ocean and atmosphere as an interactive system.

- o The responses of sea ice, major ice sheets, continental glaciers, and of world sea level to climatic change.

- o The metabolism of ecosystems accounting for changes in species, and for the exchange of H<sub>2</sub>O and chemicals with other reservoirs, in response to variations in the external environment.

In addition we need to develop the techniques of integrating ecosystem models with global models of the physical and chemical environment of the Earth, leading to eventual coupled models that describe all the basic features of the global environment. Immediate needs in this endeavor are joint agreements between disciplines as to scale and the ensuing challenges of aggregation and disaggregation of relevant data.

## TESTS

A necessary part of model development is the synergistic use of tests in natural systems to evaluate and perfect the model's performance. Many of the *observations* and *process studies* listed earlier will serve this function. In addition, one can learn much from reading the record of the past, where Nature has conducted grand experiments of her own. If we can but read it, the past history of the Earth will provide surprises that will stimulate new ideas and suggest new observations, which in turn will lead to the refinement of models and the definition of further tests. In this regard, the environmental record discussed in Chapter 2 becomes a particularly valuable resource for an IGBP. The following steps are needed to exploit it:

- o Expanded, cooperative programs of polar ice core retrieval and analysis to reconstruct the history of world temperature, atmospheric chemical and particulate properties, terrestrial vulcanism and its effect on

climate, and the history of galactic cosmic-ray flux for studies of solar and terrestrial magnetic-field variations. For some of these studies, cores will need be taken from middle- and low-latitude glaciers in areas such as the Alps, the Himalayas, and the Andes.

- o Intensification of efforts to recover and analyze sedimentary records from the seafloor from a large area of the globe for studies of past climate, ocean circulation patterns, cosmic-ray fluxes, and the nutrient chemistry of the oceans. Appropriate numerical models need also to be developed to further our understanding of the dynamics of the inferred changes.

- o Expanded efforts to collect varved sediments in lakes and estuaries, to refine their temporal resolution and to expand the regions sampled for reconstructions of past climate, biotic distributions, and the chemical and particulate content of the atmosphere.

- o Expanded efforts to determine the temporal extent and geographic coverage of the tree-ring record as a repository of information on climatic, hydrologic, volcanic, and solar history over the past several thousand years. Trees that are most sensitive to environmental stress are generally found in arid or mountainous regions that are often remote.

- o Expanded efforts to establish the record of changes in sea level; studies of tropical coral growth and deposition as an indicator of past sea level and climate.

## MODES OF INVESTIGATION

The research described in this report represents an exciting new challenge for earth and biological scientists. The opportunities for individual involvement range from participation in small, focused experiments with relatively simple hardware demands all the way to the large and technologically challenging endeavors exemplified by Earth-orbiting satellites. The need for interdisciplinary cooperation in scientific planning has been emphasized in the preceding chapters. There will be a need for similar cooperation during the design and execution of the measurements themselves. Physical, chemical, and biological data will often be required for the same locality and can often be obtained most economically using the same surface station, aircraft, ship, or satellite.

There are certain modes of observation needed in an IGBP that are worthy of particular emphasis. We see the need for a globally distributed, low-density network of surface stations for long-term measurements of atmospheric trace species. In addition, we identify the need for higher-density networks of surface stations for intensive short- and/or long-term studies of vegetation, hydrology, and sources and sinks for trace species. These networks would operate in land areas of high biological and chemical activity such as tropical forests and other critical ecosystems. The need for stations similar to both of the above types of networks has already been emphasized as an essential element in the



proposed Global Tropospheric Chemistry Program.

For the ocean, the acquisition of a global data set and a long-term record is even more challenging than for the land or atmosphere. Regular sampling schemes that include more frequent visits to the remoter parts of the world's oceans and efficient methods for sampling will all be necessary in order to provide physical, chemical, and dynamical data at the required temporal and spatial resolutions.

While long-term measurements are an essential feature of an IGBP, a wide variety of shorter-term experiments will also be necessary. For example, experiments designed to identify the currently elusive sources of atmospheric methane and nitrous oxide and to understand better the processes responsible for the formation of ocean bottom water are equally important.

Satellite observations have been recognized as important potential contributors to further advances in almost all of the earth sciences. For an IGBP we emphasize specifically the essential role of satellite observations for studies of the global physical environment and global biota. However, we also emphasize that for some objectives satellite measurements alone are of limited use and that in situ measurements are essential to aid in the interpretation of remotely sensed data.

In addition to observations, an IGBP will clearly demand significant new efforts in data processing and analysis and in the further development of global models incorporating all the important biological, chemical, and physical processes. In this respect we emphasize two particular needs: first, interactions among the involved disciplines and second, intensive work in areas of particular need or current relative ignorance. One useful way to address both of these needs is to conduct focused workshops with well-defined goals at both the national and international levels.

While activities such as the launching of satellites and the development of general circulation models are capabilities possessed by relatively few countries, many other experimental and theoretical activities in an IGBP (such as surface observing networks and many aspects of data analysis) provide the opportunity for all countries with interested scientists to make fundamental and essential scientific contributions. In this respect, we emphasize that the extensive data base relevant to an IGBP should be quickly accessible to all interested scientists, as should the results of the associated analyses, models, and tests. A comprehensive data bank employing modern techniques of data storage and worldwide access is a task of great magnitude--and perhaps the largest single challenge of an IGBP. The Committee recognizes this requirement as essential to the success of the program.

## RELATIONSHIP TO OTHER PROGRAMS

There are now in progress a number of international research programs aimed at specific components of what we have called the geosphere-biosphere system. Many of these, with others now in planning stages, will continue into and indeed beyond the era of an IGBP. What is the optimum relationship between these more disciplinary programs and a multidisciplinary IGBP?

A possible model, which we reject, is a simple federation of the varied, international disciplinary programs under a single banner of coordinated research: in effect, the erection of an umbrella over all the diverse activities that study the Earth and its biota and near environment. Such an approach seems to us neither workable nor desirable, nor one that would meet the goal of understanding the Earth as a coupled system.

We propose instead a separate and more restricted endeavor, defined by a focused objective of the kind that we have developed here. An IGBP of this design would not subsume or replace other more disciplinary programs. It would communicate with and to some extent depend on them, however; and the existence of one would enhance the scientific returns of the other. The principal goal of an IGBP--to understand the Earth as a coupled, interactive system--and the new information that it seeks to find are not the primary ends of other international programs of research. Certain elements of the World Climate Research Program, the International Lithosphere Programs or an International Solar Terrestrial Program, for example, will make necessary inputs to an IGBP, and other elements will not.

A final point is the relationship of preliminary studies within this country, such as that described here, to an eventual plan for an IGBP. It is clear to all that an international program must be internationally planned and internationally agreed on if it is to be internationally executed. At this time the International Council of Scientific Unions is considering the implementation of an International Geosphere-Biosphere (or Global Change) Program, with inputs solicited from many nations and international scientific organizations. We hope that the recommendations developed here will be useful contributions to this great dialogue.

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