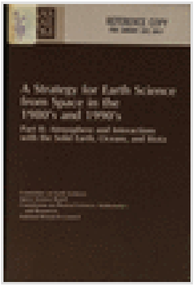

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Part II: Atmosphere and Interactions with the Solid Earth, Oceans, and Biota

Committee on Earth Sciences
Space Science Board
Commission on Physical Sciences, Mathematics,
and Resources
National Research Council

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While the responsibility for the strategy lies solely with the committee, thanks are due to each of the above individuals for their time and effort, which was always appreciated.

Contents

Executive Summary

Part II of this report of the Committee on Earth Sciences presents a strategy for the future study of the atmosphere and its interactions with the land, oceans, and biota using satellite observatories. Part I (*A Strategy for Earth Science from Space in the 1980's, Part I: Solid Earth and Oceans,* National Academy Press, 1982) earlier presented a parallel strategy for the future study of ocean dynamics, solid earth dynamics, and continental geology. Together, Parts I and II provide an overall strategy for the study of the Earth from space over the next 10 to 15 years.

In this strategy, the committee identifies scientific problems whose solution involves global measurements achievable most inexpensively by space missions alone or by a combination of space missions and other types of observational systems. The committee's strategy proceeds only as far as the definition of required measurements from spacecraft or from cooperative observing systems. It does not define specific required spacecraft or explicitly endorse any existing plans for such spacecraft. It is the committee's intention that this strategy will provide the scientific basis over the upcoming one to two decades for the design and implementation of specific spacecraft missions based on the then prevailing fiscal and space transportation constraints. Implementation of the strategy will involve acquisition of a very large volume of data, which must be carefully managed to ensure its easy availability and usefulness to the broad scientific community. An earth sciences information system must therefore be developed with particular attention to the need for interagency and international cooperation and to methods for long-term data retention.

The atmosphere is a globally pervasive fluid medium that has complex dynamical and chemical behavior. It also actively interacts with the other media in the earth system and serves to link these media faster and more directly than any other single entity. These interactions center on the ability of the atmosphere to readily exchange sensible heat, momentum, radiation, water substance, compounds of carbon, nitrogen, and sulfur, and radiatively active gases and aerosols with the land, oceans, and biota and then to rapidly transport these exchanged properties or materials over regional and global scales. Therefore, this report addresses not just the atmosphere but an interactive system comprising the atmosphere and those parts of the land, oceans, and biota that the atmosphere influences or is influenced by. The committee refers to this system as the atmosphere-land-ocean-biota system. This system possesses complex feedbacks that defy easy and immediate analysis and hamper present attempts to predict its evolution reliably.

In looking to the future, it is readily apparent that two particular scientific themes have emerged that will play important if not dominant roles in the further development of the atmospheric sciences. The first theme involves the atmosphere as a complete system with continental-scale and/or global-scale dynamic, thermodynamic, and chemical connections; the second involves the interaction of this atmospheric system with the land (including the ice caps), oceans, and biota (including man). In addition, the Earth as a planet is and always has been subject to both episodic and chronic changes. Today and in the future, considerable attention is expected to be directed at the human role in inducing changes—intentional or otherwise—that may affect the environment on a time scale as short as or shorter than a human lifetime. The ability to reliably predict the currently putative anthropogenic changes in the environment would be an achievement of great societal importance and would be of considerable scientific interest as well.

The interactive nature of the global atmosphere makes it imprudent to develop a strategy for the study of this medium that is separate from an investigation of the relevant elements of the terrestrial, oceanic, and biological realms. At the same time, the complexity of the internal processes in the atmosphere alone precludes a strategy that focuses merely on its interactions with these other realms. The committee has therefore divided its strategy into five distinct but related sections:

- Troposphere
- Stratosphere and mesosphere

- Global hydrologic cycle
- Global biogeochemical cycles
- Prediction of long-term climatic changes

To constrain its task the committee found it necessary to restrict its definition of the atmosphere to the region between the surface and the mesopause (which lies at an altitude of about 85 km).

The committee had defined three overall goals for the study of the atmosphere and its interactions with the land, ice caps, oceans, and biota:

The first goal is to determine the atmospheric distributions and cycles of mass, energy, momentum, and water vapor and of chemical constituents important to climate and to the maintenance of life.

The second goal is to understand the physical and chemical dynamics of the atmosphere and its interactions with the land, ice caps, oceans, and biota.

The third goal is to understand the evolution of the atmosphere to its present state, and to predict its future evolution on time scales less than 100 years including the effects of anthropogenic and natural perturbations.

The rationale for these goals is provided in Chapter 2.

In each of the five sections of the strategy, objectives are defined whose successful accomplishment over the next 10 to 15 years will enable important steps toward the achievement of the above goals. These objectives require satellite observations and (where relevant) supporting nonspace modes of investigation. For each objective the details of the required measurements from space are discussed. Correlative requirements for theory, data analysis, and instrument development are then provided. For each section the priority afforded a particular objective reflects both its scientific and societal importance and its feasibility, either with present technology and resources or the technology and resources expected over the next 10 to 15 years. For objectives not able to be addressed by such missions over the next 10 to 15 years, the committee identifies instrumental and/or theoretical developments required before the full potential of a space mission can be brought to bear on their accomplishment.

Based on its considerations of (1) priority and (2) balance among disciplines, the committee has defined an *essential set of objectives* for observations from space of the interactive atmosphere-land-ocean-biota system over the next 10 to 15 years.

The committee has not attempted a detailed ranking of all of the objectives in this essential set, but it has identified certain objectives that have greater priority than all others. In particular, the overriding importance, both scientific and societal, of measurements of certain elements of the global hydrologic cycle and of the causes and signals of climate change makes it essential that such measurements be included as a necessary part of the overall program for the study of the Earth from space. *The committee specifically concludes that accurate measurements of (1) the rates of precipitation, evaporation, and evapotranspiration over the global land and ocean surfaces and (2) the global trends in sea surface temperature, albedo (snow, sea ice, cloud, and vegetative cover), and radiatively important gases (in particular water vapor and ozone) and aerosols are objectives of the highest priority for the study of the atmosphere-land-ocean-biota system from space over the next 10 to 15 years.*

The interactive behavior of the atmosphere, land, oceans, and biota requires that advances in the requisite disciplines of meteorology, oceanography, hydrology, geology, and biology proceed in parallel. Therefore in addition to the objectives enunciated above, *the committee recommends that achievement of the highest-priority objectives as listed below in each of the areas of the troposphere, the stratosphere and mesosphere, the global hydrologic cycle, the global biogeochemical cycles, and the climate be an essential element in the program for study of the Earth from space over the next 10 to 15 years.* This recommendation is designed to ensure the progress required in each of the disciplines involved in the observing program. It is not intended as a statement of a minimum level of effort or as a judgment that the highest-priority objectives in each of the stated areas are of equal priority.

The highest-priority objective for the study of the troposphere from space is to accomplish each of the following:

1. *To obtain global data sets for the internal and boundary forcing processes that maintain the atmospheric circulation. The required data sets are for (i) surface wind, atmospheric temperature and humidity, and stress over the oceans, and land and sea surface temperature; (ii) precipitation, and closely related surface characterisitcs including soil moisture, snow and ice cover, and vegetative biomass; (iii) surface radiation and albedo, radiation at the top of the atmosphere; and (iv) cloud characteristics including type, amount, height, temperature, liquid water content, and radiative properties.*

2. *To obtain temporally continuous global data sets of sufficient spatial density and accuracy to determine the large-scale structure of the troposphere. The required data sets are for (i) wind, temperature, and moisture in the free atmosphere, and (ii) sea level pressure.*

The rationale for and detailed discussion of the above objective and of other important but lower priority objectives for the troposphere are contained in Chapter 4.

The highest-priority objective for the study of the stratosphere and mesosphere from space is to accomplish each of the following:

1. *To measure continuously total ozone and its vertical profile over the globe with sufficient accuracy to test theoretical predictions.*
2. *To measure simultaneously the vertical profiles of atoms and radicals involved in ozone chemistry and the source and sink species of these atoms and radicals, as a function of latitude and time of year.*

Additional important (but lower priority) objectives for the stratosphere and mesosphere are given in Chapter 5 along with supporting discussion.

The highest-priority objective for the study of the global hydrologic cycle from space is to accomplish each of the following:

1. *To measure the spatial distribution and amounts of freshwater runoff, soil moisture, precipitation, and evapotranspiration over the Earth.*
2. *To measure the horizontal extent, depth, density, liquid water content, and albedo of the world's snow cover.*
3. *To measure the horizontal extent, velocity, surface temperature, albedo, and topography of the world's sea and lake ice cover and to distinguish between different ice types.*
4. *To measure the topography of the upper and lower surfaces, thicknesses, surface areas, surface temperatures, albedo, and internal structure of the world's major glacial ice sheets and shelves.*

This objective is addressed in detail in Chapter 6 along with presentations and discussions of the important but lower priority objectives.

The highest-priority objective for the study of the global biogeochemical cycles from space is to accomplish each of the following:

1. *To measure the concentration of chlorophyll-a in the world's oceans.*
2. *To measure the areal extent and the change in areal extent of terrestrial biomes.*
3. *To measure the biomass densities in the various terrestrial biomes.*
4. *To measure the magnitudes of the terrestrial and oceanic sources and sinks for radiatively and chemically important tropospheric trace gases, in particular CO_2, CO, CH_4 and other hydrocarbons, N_2O, NH_3, $(CH_3)_2S$, H_2S, OCS, and SO_2.*

This objective and related lower priority objectives are discussed in Chapter 7. The committee emphasizes that the above highest-priority objective for the global biogeochemical cycles requires important supporting nonspace observations in order to be achieved.

The highest-priority objective for the study of long-term climatic changes from space is to accomplish each of the following:

1. *To measure the long-term global and regional trends in external and internal climate forcings: the variables that must be measured are the solar flux, the radiative fluxes at the top of the atmosphere, radiatively important trace gases and aerosols, and certain land surface properties (vegetation cover, soil moisture, albedo, and emissivity).*
2. *To measure the long-term global and regional changes in climate: the variables that must be measured are surface and tropospheric temperatures, precipitation, water vapor, and cloud, snow, and ice cover.*

Detailed discussion of this objective is provided in Chapter 8.

The dynamics of the oceans, which was addressed in the earlier report from the committee, is an important process in the overall interactive atmosphere-land-ocean-biota system. *The committee therefore augments the above list of highest-priority objectives with the highest-priority objective for ocean dynamics defined in the earlier report.*

The highest-priority objective for the study of ocean dynamics from space is to accomplish each of the following:

1. *To measure the time-variable sea surface elevation.*
2. *To measure the time-independent sea surface elevation relative to the geoid.*

In defining the above highest-priority objectives, *the committee has specifically assumed that the current operational meteorological satellite system including both geostationary and polar-orbiting satellites will be maintained at least at its current level in order to continuously measure the state and circulation of the atmosphere.*

The principal client national agencies for the committee's strategy are NASA and NOAA, with whom will lie the ultimate responsibility for mission design and implementation. With regard to the types of missions that should be flown, *the committee is especially concerned that the space operations and transportation capabilities will be available in the future to enable NASA and NOAA to implement this proposed strategy.*

In particular, the earth sciences have certain special needs for space operations that must be satisfied. *Polar, near-polar, and geostationary orbits are all required. Also, two types of missions are necessary: long-term (perhaps multisatellite) missions that address decadal trends in the earth system and shorter term missions that address specific scientific and associated instrumental development objectives. Certain missions will demand high power and large data transmission rates.*

The interdisciplinary nature of the research addressed in this report poses a challenge both to scientists and to NASA, NOAA, and other relevant federal agencies. The committee is aware of NASA's plans for a Global Habitability Program, which could potentially aid in the nurturing of the necessary interdisciplinary research. The committee does not regard the strategy in this document as being necessarily restricted in its implementation to agencies of the United States. International cooperative endeavors, to the extent that they address the strategy in a timely manner and represent an equitable sharing of costs and benefits, should be encouraged to the greatest degree possible.

Inherent in the strategy outlined in this report is the continued maintenance of specific research programs in the atmospheric and related sciences over the next 10 to 15 years. In some areas such as global biology, significant growth is needed in the current program to ensure optimal use of the data obtained. The committee's strategy is to a considerable extent derived from the knowledge gained from these traditional research programs. As the strategy unfolds, these programs will be important recipients and interpreters of the new knowledge gained. Existing activities within these programs include ground-based, airborne, and satellite observations; instrumental development and deployment; acquisition, storage, and dissemination of large volumes of data; theoretical studies including general circulation and climate models; and a wide variety of laboratory experiments.

Improved understanding of the complex physical, chemical, and dynamical processes involved in the interactive atmosphere-land-ocean-biota system will demand considerable improvements in our current theoretical models of this global system. *Further development of these models must proceed in conjunction with the acquisition of new data.* Model development and data acquisition must be an interactive process with the models suggesting new measurements and the measurements being used to constrain, test, and improve the models.

1 Introduction

Atmospheres are known to be present on seven planets and one moon in our solar system. The Earth's atmosphere is unique because the majority of its components are products of biological activity on the surface and in the ocean. The atmospheric circulation and climate of the Earth also differ markedly from those on the other planets. These differences are not manifestations simply of a differing rotation rate and proximity to the sun but also of the ubiquity of water in all three phases and the presence of the oceans and vegetation on the Earth.

Part II of this report of the Committee on Earth Sciences presents a strategy for the future study of the Earth's atmosphere and its interactions with the biota, oceans, and solid surface using satellite observatories. Part I *(A Strategy for Earth Science from Space in the 1980's, Part I: Solid Earth and Oceans)* earlier presented a parallel strategy for the future study of ocean dynamics, solid earth dynamics, and continental geology. Parts I and II are submitted together by the Committee on Earth Sciences in response to the request from the Space Science Board to develop an overall strategy for the study of the Earth from space over the next 10 to 15 years.

In Part I the current state-of-knowledge of the planets was reviewed. The study of the Earth as one of the planets with important similarities and differences to other solar system objects was emphasized. The committee concluded that *the primary scientific goals for the further investigation of the Earth are to determine the composition, structure, and dynamics of the solid planet, its oceans and atmosphere, and its* *surrounding envelope of charged particles and fields; to characterize the systems of living organisms and their interactions with their environment; and to understand the processes by which the Earth formed as a planet and evolved to its present state*. It was also concluded that observations from satellites can and should play an important role in the study of the Earth over the next decade and that the Earth is an object worthy of intensive scientific study quite apart from the fact that mankind happens to inhabit it. These conclusions concerning the Earth as a whole are also valid specifically for its atmosphere and for the interactions of its atmosphere with the biota, oceans, and land.

The study of the atmosphere as an exact science is a phenomenon of the twentieth century and in particular of the last 35 years. Its development as an exact science has been fueled not only by an intrinsic desire to understand the basic dynamics, physics, and chemistry of the atmosphere but also by a more practical wish to predict and to some extent control those aspects of the atmosphere that affect our immediate health, sustenance, and well-being; hurricanes, tornadoes, blizzards, floods, avalanches, droughts, air pollution, sunburn, and acid rain are occurrences just as tangible to the nonscientist as to the scientist. These phenomena are important not just to humans but also to all other life forms on the Earth's surface.

The rapid rate of growth of fundamental knowledge in this area over the past few decades has been sparked by some important revelations including the discovery of the role of baroclinic instability in forcing atmospheric motions, the application of computers to the numerical integration of the equations of motion, the implementation of satellite observatories to probe and characterize the global atmosphere, and the recognition of the sensitivity of the atmospheric ozone layer to remarkably small amounts of man-made chemicals. Over the past decade in particular, it has become apparent that the atmosphere is, in a genuinely nontrivial sense, a global-scale entity with complex dynamical, physical, and chemical connections that link tropical with temperate latitude, southern with northern hemisphere, and lower with upper atmosphere.

As impressive as progress has been, there remain a number of outstanding problems in the atmospheric sciences. Dependable 24-hour predictions of severe storms and of the duration and amounts of precipitation are still not available. Our understanding of the physical dynamics of persistent features of the weather such as blocking highs and major storm tracks is still insufficient and severely limits our ability to predict atmospheric behavior over monthly to seasonal time scales.

On time scales of a year to decades, we do not yet possess a comprehensive global model that would enable reliable assessment of the potentially detrimental impact of natural phenomena (e.g., volcanoes, sea surface temperature anomalies, fluctuations in ice and snow cover, and natural variations in vegetative type and cover) and anthropic phenomena (e.g., deforestation and fossil fuel combustion) on regional and global climate. On the same time scales, we are ignorant of those details of the global carbon dioxide cycle and global ozone budget that would enable quantitative predictions of future carbon dioxide and ozone concentrations in the atmosphere with their concomitant effects on global climate and ultraviolet dosages at the Earth's surface.

In looking to the future, it is readily apparent that two particular themes have emerged that will play important if not dominant roles in the further development of the atmospheric sciences. The first theme involves the atmosphere as a complete system with continental-scale and global-scale dynamic, thermodynamic, and chemical connections; the second involves the interaction of this atmospheric system with the oceans, the land (including the ice caps), and the biota (including man). Several phenomena illustrating these themes are specifically addressed in this report. Large-scale dynamic and thermodynamic connections and ocean-atmosphere interactions are exemplified by the Southern Oscillation. This oscillation is a quasiperiodic climatic phenomenon centered over the tropical and subtropical Pacific and Indian oceans but linked to other parts of the tropics, to weather over North America, and to El Nino, a dramatic episodic warming of the ocean off the west coast of South America. Large-scale chemical connections and biota-atmosphere interactions are exhibited in the atmospheric nitrogen oxide cycle, in which nitrous oxide produced by microorganisms at the surface is transported into the upper atmosphere, where it leads to catalytic destruction of ozone, which leads in turn to increased ultraviolet irradiation of surface biota.

We have a gathering appreciation of the atmosphere as a system interacting in important ways with other terrestrial systems. This has led to the realization that we are ignorant of many pertinent aspects of these other systems that are necessary to quantitatively address these interactions. Botanists cannot currently provide meteorologists with a predictive model of evapotranspiration by large areas of the Earth's surface that incorporate various types of vegetation. Glaciologists have insufficient knowledge of the dynamics and thermodynamics of the polar sea ice sheets to provide climatologists with a predictive model for polar albedo. Oceanographers lack a quantitative understanding of the factors contributing to sea surface temperatures and to the exchange of momentum between atmosphere and ocean, both of which are important boundary conditions for atmospheric models. The effective study per se of the terrestrial systems that mesh with the atmosphere is thus an important and necessary corollary to future progress in atmospheric science itself.

The investigation of global-scale phenomena proposed by the Committee on Earth Sciences in this report demands global-scale observing systems with all their attendant requirements. A detailed investigation of the use of earth-orbiting satellites therefore has been an integral part of the preparation of this strategy. The committee concludes that satellites provide the best chance and most cost-effective way of answering a significant number (but certainly not all) of the major questions facing the atmospheric and related sciences at this time. The launching and maintenance of research satellites and the development of instrumentation for them are, however, activities that demand long-term planning and are not insignificant drains on the national purse. For this reason, great care is required to ensure that the resources available for earth-orbiting missions are directed toward solution of the most important scientific problems and that the resultant missions proceed in an order and at a pace concomitant with the timely solution of these problems. The committee also recognizes that space missions must be coordinated with equally orderly and sensibly paced programs for relevant ground-based, aircraft, and balloon-borne measurements and for relevant theoretical studies of the atmosphere, hydrosphere, cryosphere, and biota.

In its strategy, the committee deliberately identifies scientific problems whose solution involves global measurements achievable most inexpensively by space missions alone or by a combination of space missions and other types of observational systems. This in no way should be interpreted as downgrading problems that can be solved most cost-effectively without any space component whatsoever. The deemphasis of these latter problems here stems solely from the fact that they generally can be tackled without the special combination of decadal planning and commitment of significant national resources that typifies the problems addressed in this strategy.

The committee began its task with the definition of overall goals for the atmospheric sciences. The degree to which the various divisions and subdivisions of the subsequently defined strategy contribute to the achievement of these goals then provides a measure of the priority afforded these various parts. As a matter of convenience and from intellectual motivation, the strategy is presented in five sections: (1)

troposphere, (2) stratosphere and mesosphere, (3) global hydrologic cycle, (4) global biogeochemical cycles, and (5) long-term climate changes and predictions. In each section the important intersystem interactions—for example, between the atmosphere and ocean, atmosphere and biota, biota and hydrosphere, troposphere and stratosphere—are specifically addressed in addition to the intrasystem processes.

In each of the above sections, specific goals are identified. A list of objectives are then defined whose successful accomplishment over the next 10 to 15 years will enable important steps toward the achievement of these goals. Both goals and objectives are, to the greatest extent possible, placed in order of their priority. In particular, the committee identifies primary objectives that are intended to form the basis for defining and ordering individual space missions and their accompanying nonspace components. It also defines secondary objectives whose accomplishment should be interpreted as enhancing the value but not solely justifying the existence of a particular space mission. It is emphasized that certain missions will need to be accompanied or preceded by specific nonspace investigations if these particular missions are to achieve their primary objectives. It is also emphasized that the committee's definition of objectives in the area of meteorology is contingent upon continuance of the existing global operational meteorological satellite system. Certain other objectives (e.g., concerning climate) necessitate continuous observations over decadal time periods, which may require a sequence of satellites with due attention to intercalibration. The committee also notes that certain objectives, while perhaps ultimately approachable with space missions, could not be effectively addressed by such missions over the next 10 to 15 years. For these objectives, the committee identifies instrumental and/or theoretical developments required before the full potential of a space mission can be brought to bear on their accomplishment.

The committee's strategy proceeds only as far as the definition of required measurements from spacecraft or from cooperative observing systems. It does not define specific required spacecraft or explicitly endorse any existing plans for such spacecraft. The committee intends this strategy to provide the scientific basis over the upcoming decade for the design and implementation of specific spacecraft missions based on the then prevailing fiscal and space transportation constraints. *The client national agencies for this strategy are NASA and NOAA, with whom will lie the ultimate responsibility for mission design and implementation.* This approach means that the strategy will have the advantage of a meaningful lifetime distinct from the year-to-year vagaries injected by the aforementioned constraints. The Committee on Earth Sciences is vitally concerned with the achievement of the primary scientific objectives and will support space missions that will achieve these primary objectives.

The committee has recognized that its task is at first sight formidable. It encompasses some diverse disciplines ranging from fluid mechanics to chemical kinetics, from plant metabolism to cloud physics, and from mesoscale to global-scale problems. This task, fortunately, was alleviated in part by the existence of three recent reports addressing the present state of knowledge and key problems for future attention in the atmospheric sciences: *The Atmospheric Sciences: National Objectives for the 1980's* (National Academy of Sciences, 1980), *Carbon Dioxide and Climate: A Second Assessment* (National Academy Press, 1982), and *Causes and Effects of Stratospheric Ozone Reduction: An Update* (National Academy Press, 1982). These reports even together do not constitute prioritized strategies for addressing all the key problems of the future, but they do contain important elements or portions of strategies that, to the extent they are relevant, were taken into account in this committee's deliberations.

The committee's task was also aided by a series of tutorials delivered to it by invited experts in various areas of the atmospheric and related sciences (see Acknowledgments). These tutorials proved most helpful in the formulation of goals, objectives, and priorities. While the committee was the ultimate arbiter during the strategy formulation, the contributions of these individuals were often germinal and always appreciated.

To constrain its task the committee found it necessary to restrict its definition of the atmosphere to the region between the surface and the mesopause (which lies at an altitude of about 85 km). The choice of this particular upper boundary is in part motivated by the fact that the physics of the atmosphere begins to change in a fundamental sense above the mesopause, with the need to consider atmospheric ionization, molecular diffusion, electric and magnetic fields, and the relatively close connection to solar behavior exhibited by these high regions of the atmosphere. In addition, two strategies addressing these higher regions already exist: *Solar-Terrestrial Research for the 1980's* (National Academy Press, 1981) and *Solar System Space Physics in the 1980's: A Research Strategy* (National Academy Press, 1980). The committee emphasizes, however, that there are important chemical and dynamical processes that link the atmospheric regions above and below 85 km and that the artificial division of the atmosphere at this altitude should not be construed as a lessening of the importance of these coupling processes.

Inherent in the strategy outlined in this report is the continued maintenance of specific research programs in the atmospheric and related sciences over the next 10 to 15 years. This strategy is to a considerable extent derived from the knowledge gained from these traditional research programs and, as the strategy is implemented, these programs will be important recipients and interpreters of the new knowledge gained. These existing programs include basic research in meteorology, oceanography, biology, and geology; ground-based, airborne, and satellite observations; instrumental development and deployment; acquisition, storage, and dissemination of large volumes of data; theoretical studies including general circulation and climate models; and a wide variety of laboratory experiments. The committee's conclusions concerning required levels of effort in these and other supporting program activities are included in this report. Its strategy will require, in particular, significant growth in some of the existing programs. For example, there is considerable need for a more vigorous research program devoted to global biology (see *Towards a Science of the Biosphere,* National Academy Press, 1985).

Finally, the study of the atmosphere has been and will continue to be an endeavor involving many nations; specific international organizations, in particular the World Meteorological Organization and the International Union of Geodesy and Geophysics, have sponsored many cooperative endeavors in the atmospheric sciences. The committee does not regard the strategy in this document as being necessarily restricted in its implementation to agencies of the United States. International cooperative endeavors, to the extent that they address the strategy in a timely manner and represent an equitable sharing of costs and benefits, should be encouraged to the greatest degree possible. The committee's specific statements on international cooperation with particular emphasis on Earth-orbiting missions also form a part of this report.

2
Scientific Goals

Atmospheric science is one of those sciences upon which society possesses legitimate liens on its conduct and progress. There are many specific societal goals of which we must be fully aware: farmers in the Grain Belt of North America would like to see reliable short- and long-term predictions of rainfall; residents on the coasts of Florida, Louisiana, and Texas desire accurate forecasts of hurricane pathways; cities in the Northeast would benefit considerably from prescience of blizzards; and so on. However, progress toward such goals when they are treated as individual targets is frustrated by the complex interrelationships between various atmospheric phenomena, which have already been noted in the Introduction. In practice we must therefore consider attainment of these societal goals as products of, rather than antecedents to, the achievement of purely scientific goals.

The committee has defined three overall and interrelated goals for the study of the atmosphere and its interactions with the land, ice caps, oceans, and biota. These three goals have equal priority.

The first goal is to determine the atmospheric distributions and cycles of mass, energy, momentum, and water vapor and of chemical constituents important to climate and to the maintenance of life. This goal recognizes that observations to date are still insufficient to provide a complete picture of the spatial and temporal behavior of the global atmosphere. Of particular concern is the general lack of reliable data at the required resolutions and over the necessary time scales for the atmosphere over oceans and over remote uninhabited land areas, for the cryosphere and biota, and for the ocean surface. Acquisition of this global data base is a fundamental requirement for the advancement of atmospheric science. The important role to be played by satellite observations in achieving this goal is quite apparent.

The second goal is to understand the physical and chemical dynamics of the atmosphere and its interactions with the land, ice caps, oceans, and biota. This goal recognizes that we still are not cognizant of the workings of many phenomena in our environment. Mesoscale dynamics, tropical- extratropical interactions, sea ice maintenance, biological sources and sinks, and air-sea interaction exemplify subjects needing future attention. In approaching this goal the committee recognizes that while the atmosphere on the shortest time scales can often be studied as a closed system, at longer time scales it becomes linked in an important way with the oceans, land, ice caps, and living material. In addition, achievement of this goal will necessitate specific interaction between disciplines as diverse, for example, as geophysical fluid dynamics and plant metabolism.

The third goal is to understand the evolution of the atmosphere to its present state, and to predict its future evolution on time scales less than 100 years including the effects of anthropogenic and natural perturbations. This goal recognizes the societal need for accurate forecasting of weather and climate. It also recognizes the fact that both man and nature are chronically or episodically perturbing the atmosphere in ways that could conceivably alter the future climate. The El Chichon volcano, in 1982, injected large amounts of dust into the stratosphere, and the radiatively active biogenic gases CO_2, $CFCl_3$, CF_2Cl_2, CH_4, and N_2O are currently increasing at rates of 0.4, 6, 6, 2, and 0.3 percent per year, respectively, in the atmosphere—we want to predict the long-term effects of these changes on our environment. Achievement of this goal dictates development of sophisticated computer models containing physically realistic descriptions of atmospheric, and relevant oceanic, cryospheric, and biological processes.

3
Framework for the Strategy

The atmosphere is a globally pervasive fluid medium that has complex dynamical and chemical behavior. It also actively interacts with the other media in the earth system and serves to link these media faster and more directly than any other single entity. Figure 3.1 illustrates some of the more important interactions. These interactions center on the ability of the atmosphere to readily exchange sensible heat, momentum, radiation, water substance, compounds of carbon, nitrogen, and sulfur, and radiatively active gases and aerosols with the land, oceans, and biota and then to rapidly transport these exchanged properties or materials over regional and global scales. Therefore the committee's strategy addresses not just the atmosphere but an interactive system comprising the atmosphere and those parts of the land, oceans, and biota that the atmosphere influences or is influenced by. The committee refers to this system as the atmosphere-land-ocean-biota system. All of the above exchanged quantities are of fundamental importance to the dynamics and chemistry of the atmosphere. At the same time, the exchanges of sensible heat, momentum, radiation, water substance, and aerosols are also of fundamental importance to the ocean and land surface; and the exchanges of carbon, nitrogen, sulfur compounds, and water substance are also of fundamental importance to the biota. The overall atmosphere-land-ocean-biota system thus possesses complex feedbacks that defy easy and immediate analysis and hamper present attempts to predict its future evolution reliably.

This strategy presents the scientific objectives for the investigation

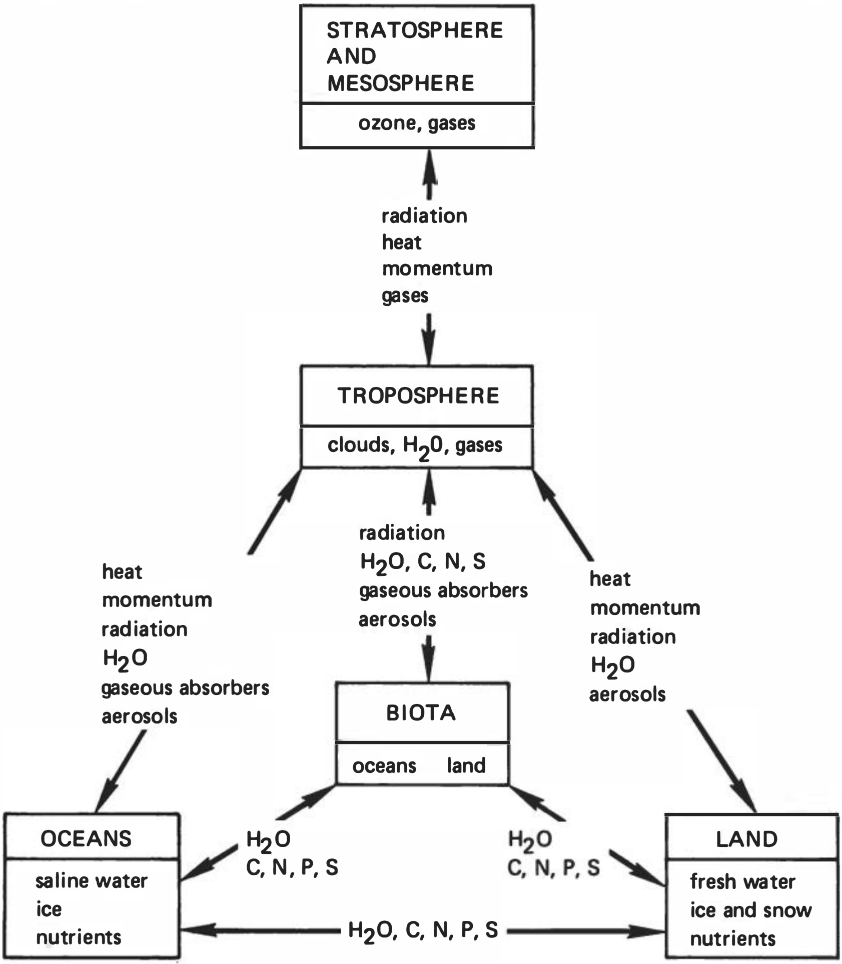


FIGURE 3.1 Dominant interactions between the atmosphere, land, oceans, and biota.

from space of atmospheric circulation, global climate, atmosphere-ocean interaction, the Earth's water and ice budget, and major biogeochemical cycles. Together with Part I of this report, it completes the full strategy for the integrated scientific study of the Earth from space for the next decade.

The interactive nature of the global atmosphere makes it imprudent to develop a strategy for the study of this medium that is separate from an investigation of the relevant elements of the terrestrial, oceanic, and biological realms. At the same time, the complexity of the internal processes in the atmosphere alone precludes a strategy that focuses merely on its interactions with these other realms. The committee therefore has divided its strategy into five distinct but related sections. These will be discussed, one by one, in Chapters 4 through 8.

The first two sections are devoted to the atmosphere itself. For convenience, the committee divides the atmosphere into (1) the troposphere (Chapter 4), and (2) the stratosphere and mesosphere (Chapter 5), with the tropopause being a natural interface between the two parts. The strategy delineated in the chapters on these two sections addresses not only the internal properties of the atmosphere but also the boundary properties that govern the exchanges between the atmosphere and its sister realms, which are important for understanding the atmosphere itself.

The third and fourth sections (Chapters 6 and 7, respectively) address the major materials—namely, water substance, and compounds of carbon, nitrogen, phosphorus, and sulfur—that are exchanged between the atmosphere, land, oceans, and biota. These materials are all fundamental to life on our planet, and some of them also play important roles in terrestrial, marine, and atmospheric processes. The third section is devoted specifically to global hydrology and glaciology and includes consideration of both the morphology, physics, and dynamics of the major fresh-water reservoirs (the hydrologic cycle) as well as ice in the sea. The fourth section specifically addresses the nature and chemistry of the major relevant reservoirs of the biotic elements carbon, nitrogen, phosphorus, and sulfur (atmosphere, soil, biota, oceans, sediments) and the fluxes between them of these biotic elements (the biogeochemical cycles). In both sections, internal atmospheric and oceanic processes, biota, and rivers play central roles in determining fluxes in the relevant cycles. Understanding, in particular, the integrated contributions of the biota to the global cycles of water substance and compounds of carbon, nitrogen, phosphorus, and sulfur poses a challenge of considerable magnitude, which must be met over the next decade or two.

The Earth as a planet is, and always has been, subject to both episodic and chronic changes. Today, considerable attention is being directed at the human role in inducing changes—intentional or otherwise—that may affect the environment on a time scale as short as a human lifetime. The ability to predict reliably the currently putative anthropogenic changes in the environment would be an achievement of great societal importance and would be of considerable scientific interest as well. The proposed study of the atmosphere, land, oceans, and biota may, if properly formulated and directed, lead to improved reliability in the prediction of some of the more important factors in the human environment, namely, the conditions of temperature, rainfall, and sunlight in the inhabited or potentially habitable regions of the world that serve to define the climate of these regions.

The committee has recognized the ability to make accurate predictions of climate on time scales less than 100 years as one of the three overall scientific goals for the study of the global atmosphere-land-ocean-biota system. These climatic predictions will require not only advancements in the subjects addressed in the first four sections of this strategy but also advancements in our understanding of the time derivatives in the global system. A fifth section (Chapter 8) is therefore devoted to the study and prediction of long-term climatic changes. This fifth section addresses both the need to identify and quantify the changes that are occurring and the need to develop a level of understanding of the working of the climate system sufficient to develop accurate predictive capabilities.

The five chapters dealing with the individual sections of the strategy are similarly structured. A discussion of the present state of knowledge and outstanding problems is followed by a statement of the overall scientific goals relevant to the section. Specific observational objectives are then defined involving space-borne and (where relevant) supporting nonspace-borne modes of investigation. For each objective the details of the required measurements from space are discussed. Correlative requirements for theory, data analysis, and instrument development are then provided. In each section the priority afforded a particular objective reflects both its scientific and societal importance and its feasibility, either with present technology and resources or with the technology and resources to be expected over the next 10 to 15 years.

The interactive behavior of the atmosphere, land, oceans, and biota demands that advances in the requisite disciplines of meteorology, oceanography, geology, and biology proceed in tandem. *The committee recommends that achievement of the highest-priority objective in each of the areas of the troposphere, the stratosphere and mesosphere, the global hydrologic cycle, the global biogeochemical cycles, and the climate be an essential element in the program for study of the Earth from space over the next 10 to 15 years*. This recommendation is designed to ensure the progress required in each of the disciplines involved in the program. It is not intended as a statement of a minimum level of effort or as a judgment that the highest-priority objectives in each of the stated areas are of equal priority.

The scientific importance of a particular objective can be assessed on the basis of criteria such as (1) does it make a major contribution to a particular discipline? (2) does it make contributions to several disciplines? and (3) does it involve the first look at a particular phenomenon with a high probability of yielding important new knowledge? A judgment of societal importance can be based on the way a particular objective is relevant to human health, safety, sustenance, and quality of life. Combining these assessments of scientific and societal importance with judgments of the feasibility (both technological and fiscal) of the proposed objective can then produce in principle an overall priority listing of the objectives.

In practice, however, the many subjective decisions required, including the weighting to be placed on the separate scientific, societal, technological, and fiscal rankings, make such an ordering procedure arbitrary. Nevertheless, the committee has identified certain objectives for measurements from space that possess very high priority irrespective apparently of the subjective nature of the ordering process. In particular, the overriding importance, both scientific and societal, of measurements of certain elements of the global hydrologic cycle and of the causes and signals of climate change makes it essential that such measurements be included as a necessary part of the overall programs for the study of the Earth from space. *The committee specifically concludes that accurate measurements of (1) the rates of precipitation, evaporation, and evapotranspiration over the global land and ocean surfaces and (2) the global trends in sea surface temperature, albedo (snow, sea ice, cloud, and vegetative cover), and radiatively important gases (in particular, water vapor and ozone) and aerosols are objectives of the highest priority for the study of the atmosphere-land-ocean-biota system from space over the next 10 to 15 years.* The accurate determination of precipitation rates from space may not at the moment be technologically feasible, but the high priority afforded such a determination mandates a program of development aimed at achieving and implementing the necessary technology over the next 10 to 15 years. The committee further notes that a knowledge of the distribution and radiative properties of atmospheric aerosols is needed not only to determine their effects on climate but also because of their impact on the opacity of the atmosphere. In particular, aerosols contaminate the radiances that are used to obtain the primary atmospheric and surface properties of interest.

In defining the above highest-priority objectives, *the committee has specifically assumed that the current operational meteorological satellite system including both geostationary and polar-orbiting satellites will be maintained at least at its current level in order to continuously measure the state and circulation of the atmosphere.*

4
Goals and Objectives for the Troposphere

INTRODUCTION

The troposphere is the lowest 85 percent or so of the total mass of the atmosphere. It is where we live and where weather, as we normally think of it, occurs. It is also the region where the atmosphere interacts across its lower boundary with the other parts of the climate system: the oceans, the cryosphere, and the surface of the Earth including its biosphere.

It has long been recognized that weather knows no geographical or political boundaries, and that weather and climate are intrinsically global phenomena. Monitoring from space is the only feasible approach for obtaining the needed global perspective. Nonetheless, even in the absence of space-based observations, a huge and reliable ground-based monitoring system exists as part of the World Weather Watch (WWW), endorsed and overseen by the World Meteorological Organization. The WWW has three primary components: the Global Observing System (GOS), the Global Telecommunication System (GTS), and the Global Data Processing System (GDPS).

Comprehensive sets of measurements are continually being taken from stations all over the world as part of the GOS. For the most part, these stations are located on the continents of the northern hemisphere. Space-based observations provide additional vital information over the rest of the globe, including the otherwise poorly sampled oceans. At present, these satellite data are obtained from a series of geostationary satellites, including two from the United States, and two U.S. polar-orbiting sun- synchronous satellites. All of the observations are fed into the GTS and received by national and regional weather centers for processing. There, the observations are merged and assimilated into computer-based models to produce the best possible analysis of the current state of the atmosphere. Although problems remain on how best to handle the vast quantities of data and to integrate their different types, optimal analyses can be achieved only if all the data are assimilated together. It is in this context that the worth of new observations from space must be placed and evaluated.

Phenomena in the atmosphere can be loosely classed as either "weather" or "climate." Weather consists of behavior that develops over a period of several days primarily from internal instabilities within the atmosphere (these instabilities are mainly of the baroclinic, barotropic, and convective type) and from forcing from the surface (for example, terrain variations and land-sea contrasts). Climate has often been regarded merely as the average weather, and in this sense it is mostly determined by factors that are external to the dynamics of the atmosphere such as solar radiation, the Earth's orbital geometry, the distribution of land, mountains, and sea, and the composition of the atmosphere. In fact, however, climate includes in its definition not only the average conditions but also the variations and extremes that characterize the evolution of the state of the atmosphere over periods of seasons and beyond.

Recently, this broader view of climate has begun to blur the distinction between climate and weather. Thus it has become increasingly recognized that many of the same processes that produce climate variations are also important in affecting weather and vice versa. It is now well established that the growth of small perturbations associated with the instabilities within the atmosphere makes detailed weather patterns inherently unpredictable beyond about 3 weeks, and weather therefore introduces a large noise component—called climatic noise—into the climate "signal." Nonetheless, processes that accompany weather, such as the redistribution of momentum, moisture, and heat by processes within the atmosphere or by exchange with the surface, are vital components of the climate system.

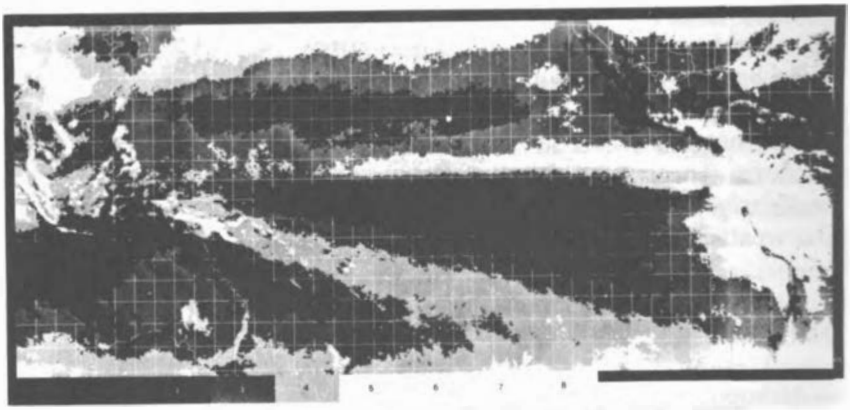
Viewing weather and climate in this way, one quickly becomes aware that a complete understanding of them requires that the atmosphere be treated as part of a larger system that includes the oceans, sea ice, surface waters, and biota. Although the degree of coupling among these different elements is a function of time scale, the coupling proceeds in all directions, which requires that climate problems, for instance, be dealt with in an interdisciplinary fashion. Examples of these interactions abound, but two will illustrate the point. The first is the coupling between the atmosphere and the oceans in the phenomena known as the Southern Oscillation and El Niño, whose time scale of several years makes it especially relevant for climate problems (*El Niño and the Southern Oscillation: A Scientific Plan*, National Academy Press, 1983). The mechanisms operating in the Southern Oscillation, however, may also be important in shaping certain weather patterns. The second example is the coupling between precipitation and surface characteristics (such as soil moisture), which can affect the weather and thereby the climate in a region.

The Southern Oscillation and El Niño

Although the vagaries of global climate at first glance seem random, there is a strong signal that stands out above the noisy background of short-term climate change. This signal is loosely referred to as the Southern Oscillation (SO). Traditionally, it has been regarded as primarily comprising a large-scale seesaw of atmospheric mass between the Pacific and Indian oceans in the tropics and subtropics. The oscillation is irregular, but its preferred period lies in the range of 2 to 7 years. It is associated with interannual variations of the monsoon over India, shifts in the Intertropical Convergence Zone (ITCZ) and South Pacific Convergence Zone (SPCZ) over much of the equatorial Pacific Ocean (see Figure 4.1), and "teleconnections" that link atmospheric and oceanic conditions in the tropical Pacific to conditions in other parts of the tropics and to weather over North America and elsewhere. Related changes also occur in various other regions of the world's oceans. The most dramatic of these appears in the equatorial Pacific Ocean and is commonly termed El Niño, an anomalously large warming of the coastal waters off South America, a phenomenon often damaging to the local fishery.

The SO and its family of related phenomena make up the largest signal in short-term global climate variability. Because of the involvement of the oceans, the characteristic time scale of the phenomenon is long enough that various elements of its early evolution may be useful in predicting subsequent changes in global climate. In the last few years, statistical relationships between elements of the SO and North American climatic anomalies have been used in rudimentary seasonal climate prediction models. The physical concepts behind these models involve the shifts in planetary wave systems associated with the SO, which result in changes in storm tracks, surface air temperature, precipitation, and related variables.

Some aspects of the process by which the atmosphere drives the oceans, whose response, in terms of changes in heat storage and sea



Mercator Satellite Relative Cloud Cover, 1400 Local, 40°N to 40°S, Mean Octas, October 1967-1970.

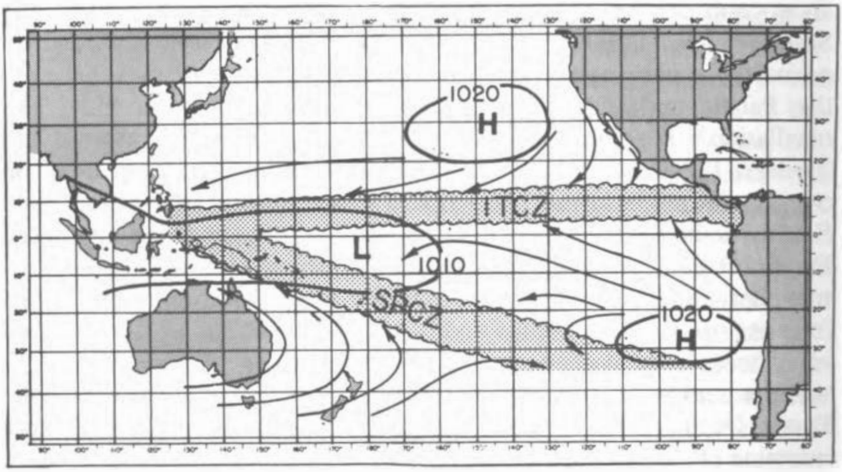


FIGURE 4.1 (a) Mercator Satellite Relative Cloud Cover, 1400 local, 40N to 40S, Mean Octas, October 1967-1970; (b) Pictorial representation of key features in (a) and of the Southern Oscillation: the Intertropical Convergence Zone (ITCZ), South Pacific Convergence Zone (SPCZ), and the annual mean sea level pressure field and schematic surface wind flow.

surface temperatures then feeds back and affects the atmosphere, are known in broad terms. The SO sequence appears to begin with a weakening of the South Pacific high and a change in the strength of the surface trade wind easterlies along the equator, just west of the dateline (see Figure 4.1). These changes signal the onset of the El Niño sequence of events within the ocean so that the warm sea surface temperatures off the coast of Peru ultimately spread into the central Pacific Ocean, where they have a profound effect on the heat budget of the atmosphere. The Walker Circulation, an east-west zonal circulation in the atmosphere, weakens; the ITCZ and SPCZ move closer to the equator and intensify, thereby diminishing the size of the equatorial dry zone; and widespread convection extends into the region east of the dateline. The increased release of latent heat results in the entire tropics becoming warmer and locally sets up anomalous vorticity sources within the atmosphere. Because during winter these are embedded in upper level westerlies, a train of large-scale atmospheric waves (so-called Rossby waves) can be set up that propagates energy downstream and into higher latitudes to produce the observed teleconnection patterns over North America and elsewhere. Along with associated changes in the jet stream, these waves alter the storm tracks of transient disturbances and therefore affect the extratropical weather regimes.

The ocean appears to be a key element in stabilizing and/or driving the SO. The ocean stores and gives up heat to fuel the atmosphere, while the latter provides momentum to the ocean to help drive its circulation and influences the fluxes of radiation and sensible and latent heat from the ocean surface. The physics and dynamics of this coupled system provide a rich set of scientific problems. Recent investigations show that the oceans and atmosphere communicate most effectively in the tropics, where the thermodynamic time scales of the upper ocean are comparable to those in the atmosphere, and the dynamic response to the wind is strongest. At higher latitudes the ocean response is more sluggish, effecting some degree of decoupling between the two media. Thus it appears that a key to understanding the global fluctuations of climate associated with the SO lies in studying the interaction between the oceans and the atmosphere in the tropics. Present knowledge indicates that this coupling is strongest in the equatorial Pacific Ocean.

Although the SO occurs on interannual time scales, the same mechanisms involved in the atmosphere may well be important in affecting the weather over extended forecast ranges (1 to 2 weeks). Thus a large-scale convective outbreak over the Pacific might foreshadow a change in the amplitude and position of a long-wave trough downstream over North America 5 to 10 days later.

Effects of Surface Characteristics on Precipitation

Evidence is accumulating that surface characteristics (albedo, roughness, vegetative cover, and soil moisture) and the atmospheric circulation interact in an important way to affect precipitation, particularly in summer. For example, with ample soil moisture, most of the solar insolation is used for evaporation rather than directly heating the soil. The resulting increase in moisture content of the atmosphere may be accompanied by circulation changes that together act to enhance the prospects for further precipitation and replenish the soil moisture. In contrast, in the absence of soil moisture, solar insolation tends to maintain hot and dry surface conditions that may feed back to the atmosphere and lead to a prolonged spell of below-normal precipitation.

Feedbacks between changes in surface characteristics and precipitation probably occur over a wide range of spatial and temporal scales, ranging from the mesoscale (horizontal scales of 10 to 2000 km) on time scales of about a day to the synoptic scales (horizontal scales greater than 2000 km) on time scales greater than a day. Thus increases in convective rainfall have been observed over irrigated areas of the Great Plains of the United States, while overgrazing and other misuse of land in the marginal climate zone of the Sahel in the early 1970's resulted in a decrease of vegetation and possibly a reduction in rainfall, which has perpetuated the drought. This feedback mechanism between soil moisture and weather is related to the manner in which subtropical desert climates are sustained, and possibly played a role in the wet summers of 1981 and 1982 and the summer droughts of 1980 and 1983 over North America. Methods to intentionally modify the climate through changes in surface characteristics have been proposed, including the building of asphalt heat islands in Venezuela, planting of tree shelters in North Africa, and creation of lakes in central Africa.

Although a few modeling studies have indicated the importance of changes in surface characteristics and precipitation and the subsequent feedbacks, much more observational and theoretical research is required. In particular, it is important to monitor changes in surface characteristics over the entire Earth over long time periods and the simultaneous changes in the global distribution of precipitation. While the problem of interaction and potential feedbacks between vegetation, soil moisture, precipitation, and atmospheric circulations on all scales is of high scientific interest by itself, the problem is also one of the most significant social issues to people of all countries as growing populations continue to press upon the limits of global agriculture and other resources.

SCIENTIFIC GOALS

The committee has identified two specific goals for the study of the troposphere over the next 10 to 15 years. *The first goal is improved understanding of the physical processes important in determining the circulation of the atmosphere on all scales, ranging from the mesoscale* *to the global scale*. This goal requires that a quantitative assessment be made of the physical processes that govern weather and climate as a function of time and space scales. Although somewhat artificial, it is useful for many purposes to subdivide the discussion of this goal into the following:

1. *The role of processes internal to the atmosphere*. This includes not only a comprehensive understanding of the distributions and cycles of mass, energy, momentum, and water vapor within the troposphere, but also a more complete understanding of the dynamical, thermodynamical, hydrological, and radiative processes, and their couplings and feedbacks. These are processes internal to the troposphere that contribute to its natural variability on a variety of scales.

Interactions occur between different parts of the atmosphere, between the northern and southern hemispheres; among the tropics, mid-latitudes, and polar regions; and between the troposphere and stratosphere. Many different kinds and scales of motion are involved. Thus major problems exist concerning the effects of convection and mesoscale systems on the large-scale circulation. The relative roles of transient versus stationary waves are inadequately understood. Much remains to be determined about the effects of topographic and thermal forcing on large-scale and mesoscale flows, the details of monsoons, and the teleconnections that result in a response in remote regions of the globe. Instabilities associated with vertical and horizontal shear and the moist thermodynamic structure of the atmosphere appear to be important in generating many mesoscale phenomena, yet theoretical understanding of these instabilities is only just beginning. Diurnal variations of atmospheric structure, boundary layer processes, and generation of fronts at the surface and in the free atmosphere are other important processes within the troposphere that are inadequately understood.

One of the most significant areas where our knowledge is lacking is in the role of clouds and moisture in the atmosphere. Water vapor and the amount, distribution, heights, and optical characteristics of clouds play a vital role in the radiation budget of the Earth. The water vapor condensed within clouds plays a major role in the troposphere's energy cycle through latent heating. Moisture is an interactive component in storm development and, through precipitation, is vital to agriculture and water resources. Clouds and precipitation therefore couple the dynamical, hydrological, thermodynamical, and radiative components of the circulation. In spite of this, our knowledge of cloud and precipitation climatology, cloud properties, and our ability to model clouds are very poor.

2. *The response of the atmosphere to surface inhomogeneities and*

changes in boundary forcing. This includes our understanding of the response of the atmosphere on global and regional scales to changes in sea surface temperature, snow and ice cover, soil moisture, chemical composition, albedo, and surface roughness and vegetation. On the large scale, particular interests include the role of heat storage and transports by the oceans and their effects on the atmosphere and the climate change induced by human activities that modify the characteristics of the surface. On the mesoscale, surface inhomogeneities associated with thermal contrasts and orography generate preferred regions of convection and produce significant mesoscale circulation systems.

3. *The response of the other components of the climate system to changes in atmospheric forcing.* A good example here is the El Niño phenomenon in the oceans. More generally, we need to understand how the atmosphere affects sea surface temperatures and oceanic heat storage, ocean currents, snow and ice cover, surface hydrology, and the biosphere.

4. *The response of the coupled climatic system.* In order to explain how climate changes come about, it is crucial to understand the entire coupled atmosphere-ocean-cryosphere-biosphere system. The Southern Oscillation-El Niño problem is one example of a strong two-way coupling between the atmosphere and the oceans. On a longer time scale, we need to understand how sea surface temperature, snow and sea ice, clouds, and the atmospheric circulation change together as the atmospheric content of carbon dioxide is increased. Modification of regional climate through inadvertent or intentional modification of the surface characteristics appears to have occurred in the past, and the importance to society of this problem merits further theoretical and observational studies.

In addition to understanding the present-day troposphere, we also wish to predict its evolution on a wide variety of time scales. *The second goal for the study of the troposphere over the next 10 to 15 years is improved prediction of weather and climate.* Methods of forecasting weather and climate depend very much on the time scale considered:

1. *Short-range weather forecasting* is concerned with the detailed evolution over a period of 0 to 3 days of individual atmospheric systems on all spatial scales, ranging from the mesoscale to the global scale. Deterministic weather prediction models use the current state of the atmosphere as a starting point and then forecast its dynamical evolution. Boundary forcings using climatological mean fields are frequently incorporated, but these are usually regarded as being of secondary importance to the initial conditions, except possibly for the mesoscale.

2. *Medium-range weather forecasting* is also concerned with the evolution of individual atmospheric systems, but now on time scales of about 3 days to 3 weeks. Knowledge of the current state of the atmosphere is again vital on a global scale, and increasing importance must be placed on anomalous and evolving boundary forcing such as changes in soil moisture, snow cover, and sea surface temperatures. The interactive nature of clouds should also be recognized.

3. *Monthly and seasonal forecasts* can no longer be concerned with the day-to-day evolution of weather systems, since there appears to be an inherent 2- or 3-week limit to the predictability of weather. This arises from the inevitable nonlinear growth of small observational errors into large-scale noise in the forecast. Nonetheless, the response of the atmosphere to inhomogeneous boundary conditions such as orography or sea surface temperature anomalies may enable some components of the atmosphere, such as the large-scale quasistationary waves, to remain predictable for several months. Such forecasts, however, would still have a large stochastic element to them arising from the unpredictable day-to-day weather fluctuations, and they should be couched in terms of probabilities. Patterns of rainfall and temperature are the traditional elements of interest, but it may also prove possible and useful to predict the nature of entire weather regimes including the frequency and distribution of storm tracks, severe winds, hurricanes, or other extreme events.

4. *Forecasts of long-term secular trends* depend to a large extent on our ability to simulate weather and climate in climate models. Increasing understanding of the climate system and how it may respond to changes such as an increase in the carbon dioxide content of the atmosphere can be achieved through controlled sensitivity experiments with models, but only if such models demonstrate great verisimilitude. Climate simulations may then enable a determination of the predictability of the system, and will provide a useful tool for planning and policy decisions. However, the very long time scales involved in this issue raise a number of new points, which are covered more fully in Chapter 8, which is devoted to long-term climate changes and predictions.

SCIENTIFIC OBJECTIVES

To advance our current understanding of the nature of tropospheric processes, a combination of observational objectives and advances in theory and modeling must be realized. Progress will be optimized if observations and theory advance concurrently, and it is within such an integrated program that space-based measurements must be utilized to be effective.

The primary scientific objectives for observation of the troposphere from space over the next 10 to 15 years in order of priority are as follows:

1. *(a) To obtain global data sets for the internal and boundary forcing processes that maintain the atmospheric circulation. The required data sets are for (i) surface wind, atmospheric temperature and humidity, wind stress over the oceans, and land and sea surface temperature; (ii) precipitation, and closely related surface characteristics including soil moisture, snow and ice cover, and vegetative biomass; (iii) surface radiation and albedo, radiation at the top of the atmosphere; and (iv) cloud characteristics including type, amount, height, temperature, liquid water content and radiative properties. (b) To obtain temporally continuous global data sets of sufficient spatial density and accuracy to determine the large-scale structure of the troposphere. The required data sets are for (i) wind, temperature, and moisture in the free atmosphere, and (ii) sea level pressure.*
2. *To obtain special high-resolution data sets to answer fundamental scientific questions concerning the generation, maintenance, propagation, and decay of mesoscale atmospheric phenomena. The required data sets are for (i) wind, temperature, and moisture in the free atmosphere; (ii) surface wind, humidity, and air temperature, and temperature of the underlying surface; (iii) precipitation, soil moisture, snow and ice cover, and vegetative biomass; (iv) type, amount, height, temperature, and liquid water content of clouds.*

The scientific significance and the measurement requirements for each of these two objectives are addressed below. These objectives address the physics and dynamics of the troposphere. Objectives that address the chemistry of the troposphere appear in Chapter 7. Since the measurement requirements for both of the above physics and dynamics objectives are closely related, they are presented in a single section, which follows immediately the discussion of the significance of these particular objectives.

Scientific Significance of the Objectives

Objective 1

(a) To obtain global data sets for the internal and boundary forcing processes that maintain the atmospheric circulation. (b) To obtain

temporally continuous global data sets of sufficient spatial density and accuracy to determine the large-scale structure of the troposphere.

First, such data sets are necessary to develop and test theories that explain the dynamics of large-scale atmospheric systems, including wave-wave interactions over a wide range of space and time scales. In addition, such observations also provide a data base for weather forecasting. Operational weather forecasting uses mathematical models of the atmosphere that are initialized with observations defining the current state of the atmosphere. Knowledge of the characteristics of the surface of the Earth over both the land and oceans is also required. These observations also provide verifications for the forecasts. The recently completed Global Weather Experiment has already demonstrated that improved forecasts require comprehensive global weather information.

Second, global observations provide an essential data base for climate studies. This data base is needed (1) to describe the atmospheric general circulation including the annual and interannual changes in its mean state and the transports of energy, momentum, and moisture associated with it; (2) to measure atmospheric and other climate variables that may be key indicators of climate changes; (3) to determine both short- and long-term changes in the various processes that force the climate system, with a view to understanding their possible causes; (4) to test and validate existing climate models; (5) to provide the basis for developing new and improved models; and (6) to support advances in theories of climate variations.

More generally, these observations provide a basis for many studies that enable progress toward the overall goal of understanding the physical processes important to weather and climate, as a function of the various time and space scales.

A detailed outline of the measurement requirements for this objective is given later. The relative importance attached to each kind of measurement is a function of time scale. However, another very important consideration, especially for climatological purposes, is the continuity of measurements. Although transitory interruptions in the flow of data certainly have an impact on individual forecasts, the effect is temporary. On the other hand, breaks in the record either through absence of observations or through absence of uniformity, changes in instrumentation, and inhomogeneities of satellite data can be devastating to establishing the climatological record. Temporal continuity is an essential ingredient for the data sets needed for climatological purposes.

Objective 2

To obtain special high-resolution data sets to answer fundamental scientific questions concerning the generation, maintenance, propagation, and decay of mesoscale atmospheric phenomena.

Mesoscale atmospheric phenomena, including thunderstorms, tornadoes, rainbands, tropical cyclones, frontal circulations and orographic waves, because of their complexity, raise some of the most challenging scientific questions of atmospheric physics. Often too small in size and too short-lived to be measured adequately by the operational observing system, they cannot be studied using conventional data. Because they generally involve nonlinear dynamics and nonlinear physics (such as changes of phase of water), they resist study by analytical methods. However, recent technological advances in remote sensing, both from space and from the ground, have made it technologically feasible for the first time to observe these systems throughout their life cycle. In addition, computers have become large and fast enough to enable the development of nonlinear numerical models with the essential physics to study mesoscale phenomena theoretically.

Although the time is not yet here for continuous measurements of the mesoscale, the time is right for obtaining special mesoscale data sets in order to advance understanding of the mesoscale phenomena and to test existing theories and models and develop improved ones. Thus field experiments to obtain comprehensive data sets on scales ranging from that of individual clouds to the synoptic scale, and conducted periodically over different parts of the Earth, are of high scientific priority during the next decade.

Measurement Requirements for the Objectives

The need for new or additional measurements from space must be assessed within the context of the ongoing World Weather Watch program, including its space-based component. In what follows, the committee has assumed that the current observing systems will be maintained at their present levels. This includes the presence of at least two U.S. geostationary satellites and two polar-orbiting satellites. As well as visible and infrared imagery, these systems provide data for determining the vertical distribution of atmospheric temperature (through infrared and microwave soundings) and winds (inferred from the motion of clouds) and some aspects of the atmospheric moisture profile. The polar orbiters interrogate remote surface stations such as drifting buoys. *For the continued scientific study of mesoscale and* *global-scale tropospheric circulations, it is necessary to at least maintain and preferably to upgrade the capabilities of the present operational satellite system*. In this context, the committee is aware of some proposals to downgrade the system, in particular, to one polar orbiter. However, the primary motivation for having two such satellites is not the increased data available from double coverage, valuable as they are, but the need for an in-orbit backup. Continuity in the climate record is essential. To be of use, the new measurements described here must have a steady base of operational observations to build upon.

Two recent studies have outlined the accuracies desired in measurements of atmospheric parameters and other components of the climate system: *Understanding Climatic Change: A Program for Action* (National Academy of Sciences, 1975) and *Energy and Climate* (National Academy of Sciences, 1977). These desired accuracies have been determined on the basis of their expected impact on numerical models and diagnostic studies of weather and climate. These measurement accuracies will be referred to below, where the areas ripe for significant advancement in the next decade are listed. While considering the following list of requirements, it is important to keep in mind the ever-increasing role that models are playing in assimilating observations. In this data assimilating mode, the models help to generate fields of atmospheric variables that are dynamically consistent. Moreover, in some instances, such as with precipitation, total diabatic heating, or vertical motion fields, the model-assimilated fields may provide the best estimate available of the true atmospheric fields. Another example is the large-scale atmospheric humidity fields that are generated in a short time by atmospheric dynamical models. As the models improve, they will play an essential part in complementing the measurement objectives given below.

The primary measurements required for the study of weather and climate in the troposphere for the next 10 to 15 years have been combined in the list below. The relative importance attached to each may vary significantly depending on the specific objective of a particular experiment.

1. Wind, temperature, and moisture in the free atmosphere.

2. Sea level pressure.

3. Surface wind, atmospheric temperature and humidity; wind stress over the oceans; land and sea surface temperature.

4. Precipitation, and closely related surface characteristics including soil moisture, snow and ice cover, and vegetative biomass.

5. Cloud characteristics including type, amount, height, temperature, liquid water content, and radiative properties.

6. Surface radiation and albedo; radiation at the top of the atmosphere.

7. Distribution and radiative properties of atmospheric aerosols.

Items 1 and 2 represent the core measurements required to define the dynamic and thermal states of the troposphere. These items, of course, form the basis of the current World Weather Watch (WWW) program. The committee emphasizes, however, that not only must the measurements be continued, but also improvements in quality and coverage must be sought. Items 3 and 4 represent, for the most part, areas where new measurement programs are needed. Together with items 5 and 6, they represent areas where some of the greatest gaps exist in our understanding of physical processes important to mesoscale weather and interannual variability. A knowledge of the distribution and radiative properties of atmospheric aerosols is needed for two reasons. First, aerosols contaminate the radiances that are used to obtain some of the other atmospheric parameters, and second, aerosols have an important effect on the climate. For instance, following a significant volcanic injection of debris and gases into the stratosphere, stratospheric temperatures may increase but, perhaps a few years later, surface temperatures decrease.

The measurements required for understanding and prediction depend upon the time and space scales of interest as summarized in Table 4.1. Items 1 through 6 are discussed in more detail below. Item 7 is discussed in Chapter 8 because of its primary importance to climate and climatic change.

Item 1

Wind, temperature, and moisture in the free atmosphere.

To determine the global atmospheric structure for studies of large-scale dynamical systems and for weather forecasting, observations are needed in three dimensions and at frequent intervals. The three-dimensional wind field is one area needing considerable improvement, especially in the tropics, where winds are essential for initializing weather prediction models. This is a high-priority item for which

TABLE 4.1 Observational Requirements for the Troposphere

Parameter	Temporal Scale	Horizontal Scale	Vertical Scale	Accuracy
Large-Scale Dynamical Studies and Weather Prediction				
Horizontal velocity V	12 h	100 km	1 km	±3 m/s
Temperature T	12 h	100 km	1 km	±1°C
Specific humidity q	12 h	100 km	1 km	±1 g/kg or ±10%
Relative humidity	12 h	100 km	1 km	±10%
Surface pressure p_s	12 h	100 km	—	±1 mbar
Sea surface temperature	1 day	100 km	—	±1°C
Land surface temperature	12 h	100 km	—	±2°C
Surface moisture availability (% of saturation)	24 h	100 km	—	±10%
Cloud cover	3-6 h	100 km	—	±5%
Top of atmosphere radiation budget	3-6 h	100 km	—	±5 W/m²
Surface heat and moisture fluxes	12 h	100 km	—	± 10 W/m²
Precipitation	daily total	100 km	—	± 10% oceans
		25 km	—	± 10% land
Snow and ice cover	See Table 6.2			
Vegetative biomass	1 month	100 km	—	±25%
Mesoscale Weather Studies (special data sets)				
Horizontal velocity V	1 h	20 km	500 m	±2 m/s
Temperature T	1 h	20 km	500 m	±1°C
Specific humidity q	1 h	20 km	500 m	±1 g/kg or ±10%
Surface pressure p_s	1 h	20 km	—	±0.5 mbar
Sea surface temperature	24 h	100 km	—	±1°C
Land surface temperature	1 h	20 km	—	±1°C
Surface moisture availability	24 h	100 km	—	±10%
Cloud properties	1 h	10 km	500 m	±10%
Precipitation	1 h	10 km	—	±10%

NOTE: Sampling should occur with the temporal and spatial scales given, and for primary atmosphere parameters, with the accuracy as shown. For climate parameters the accuracy may be achieved by averaging over longer periods, as described in the text.

suitable routine instrumentation for measurements over the oceans does not yet exist, although experimental studies are under way. These should be encouraged. Currently, low- and high-level winds are estimated by tracking cloud elements, but these observations can only be obtained where such elements exist, and their assigned heights have left much to be desired. The accuracy desired is 3 m/s every 100 km in the horizontal and 1 km in the vertical each day.

Measurements of the three-dimensional distribution of pressure, temperature, and humidity in the atmosphere are already part of the ongoing WWW program, but there are notable gaps over the oceans, and further improvements in reliability and accuracy are desirable. Optimal systems making use of both infrared and microwave sensors together have not been properly utilized. Microwave radiometers on geostationary satellites would be a useful addition to the current satellite-borne instrumentation, which would vastly improve the temporal resolution of radiometric soundings and avoid problems with clouds. Prospects for development of sensors that provide reasonable resolution are promising.

For mesoscale studies, the minimum necessary sampling interval and the horizontal and vertical scales of the measurements decrease significantly (Table 4.1). Although the exact data density (in both time and space) varies with the specific phenomenon of interest, most field studies require data about every hour over a horizontal scale of 20 km and a vertical scale of 500 m. Even higher resolutions are required for some important problems, such as the evolution of the planetary boundary layer or detailed circulations in clouds. Determination of these detailed structures probably can be done most effectively with ground-based remote-sensing systems (such as radars) and in-situ systems (such as aircraft). However, remote sensing from space has a major role to play in diagnosing the structure of the mesoscale environment on scales from 20 to 2000 km. In virtually all mesoscale studies, a detailed knowledge of the synoptic-scale flow is essential to understand the complete scale-interaction problem.

Item 2

Sea level pressure.

Measurements of sea level (surface) pressure are needed in combination with the measurements in item 1 to provide the input data set required by numerical models of the atmosphere. During the Global Weather Experiment, extensive efforts were made to obtain global data sets, and one of the most successful and useful new sets of measurements was that derived from the network of drifting buoys that telemetered their data to satellites for dissemination to remote users. The impact of the buoy data was most dramatically demonstrated over the southern hemisphere, owing mainly to greatly improved sea level pressure analyses. Not only do these data provide a surface reference level for satellite measurements, but they also can be used to estimate surface winds using a modified geostrophic relation in regions where other techniques are not useful (such as where sea ice is prevalent). Surface pressures are desired to an accuracy of 1 mbar over 100 km horizontal scales each day. This may eventually be achievable with microwave pressure sounder systems, a technique that should be explored further. In the meantime, further deployment of the proven drifting buoy system should be pursued.

On the mesoscale, high-resolution, surface pressure data are required only for special studies of a few phenomena, such as gravity waves and thunderstorm gust fronts. For these studies, a network of ground-based microbarographs is most appropriate.

Item 3

Surface wind, atmospheric temperature and humidity; wind stress over the oceans; land and sea surface temperature.

Surface winds drive ocean currents and exchange momentum with the oceans and the solid Earth. Detailed knowledge of surface wind stress is necessary therefore not only for atmospheric studies but also for oceanographic and geophysical studies. In Part I of this strategy the committee identified the measurement of oceanic wind stress as one of the primary objectives for study of ocean dynamics and the measurement of the Earth's rotation rate and polar motion as one of the primary objectives for study of solid earth dynamics.

Surface wind measurements over land are generally adequately defined for large-scale studies by the network of ground-based stations. Over oceans, observations are woefully inadequate. Cloud motion vectors provide a large amount of useful low-level wind data over many areas but are of limited usefulness in regions of deep convection. However, the relationship for converting cloud-level winds to surface winds is a complex function of time and space. Ships of opportunity and surface stations can provide "ground truth" wind data, but their spatial coverage is very limited. It appears that oceanic surface wind data can most readily be obtained by satellite-borne scatterometers, which are capable of obtaining the required accuracy of 2 m/s with a resolution of 100 km at least once per day. Detailed understanding of precisely what these instruments actually sense, however, is still lacking, and in-situ measurements and comparisons are an essential part of future developments.

Measurements of surface atmospheric temperature and humidity are needed in conjunction with the wind speed in order to estimate the surface fluxes of sensible and latent heat. Surface temperatures appear to be attainable using combinations of infrared and microwave sounders. Alternatively, direct measurements of the fluxes themselves or the air-sea temperature differences are needed. The latent heat flux is generally much larger than the sensible heat flux and is therefore more critical in determining the oceanic (and indirectly the atmospheric) heat balance, but it is more difficult to obtain. Possibilities that should not be overlooked include the use of drifting buoys as an instrument platform. The accuracy desired is 1°C for air-sea temperature differences or 10 W/m² over 100-km spatial scales in the fluxes.

Sea surface temperature, in addition to being an important parameter in estimating surface energy fluxes, is in a more general sense a vital indicator of the oceanic mixed-layer heat storage. As such, it is frequently necessary to specify sea surface temperature as the lower boundary condition over the oceans for atmospheric models. It is also important in the radiation budget and, consequently, required for studies of both the atmosphere and the oceans. This has been long recognized, and sea surface temperature analyses over the oceans are routinely produced with extensive use of satellite data. However, problems, in particular with cloud and water vapor contamination of the satellite-sensed sea surface temperatures, make improvements in accuracy desirable, and techniques for achieving this appear to be promising. The accuracy desired is 1°C at a 100-km resolution (or better, in regions of oceanic fronts) over a period of 5 days, although with a daily sampling frequency.

For mesoscale studies over land, increased temporal and spatial resolution of surface parameters is essential. Because of their importance in determining the energy fluxes into the boundary layer, measurements of ground temperature and moisture availability are most important, and measurements from space may be the most practical method of obtaining mesoscale analyses of these variables.

Item 4

Precipitation, and closely related surface characteristics including soil moisture, snow and ice cover, and vegetative biomass.

Precipitation is central to the hydrological cycle and for determining the distribution of snow, soil moisture, and salinity in the oceans. For the large-scale atmosphere, several quantities closely associated with precipitation are of interest. The rainfall rate is closely related to the latent heat release, which is a major forcing component of the atmosphere, and to the divergent component of the wind and vertical motion, which are difficult to measure directly. The distribution of moisture is important as input to prediction models and as a key variable component affecting radiation for climate studies.

The dominant release of latent heat through precipitation occurs in the tropics. Considerable efforts have been devoted to determining convective precipitation over the tropical oceans from satellites with varying degrees of success. A variety of visible, microwave, and infrared methods has been tried, and these efforts should be continued. The concept of adaptatively pointing a space-borne radar also appears promising and should be pursued. For climate purposes, the desired precipitation accuracy is 10 percent over 100 km for a 5-day period over the oceans and 10 percent over 25 km daily over land. In-situ measurements and ongoing evaluations of measurements are essential components of this research.

Closely linked to precipitation is the storage of surface moisture, in both the soil and the vegetation. Not all soil moisture is readily available to the atmosphere, and knowledge of the vegetation and ground cover is necessary to obtain estimates of evapotranspiration. Soil moisture is also of central importance to surface hydrology, as discussed in Chapter 6.

Soil moisture and vegetation also affect the albedo of the surface, and they vary strongly with the seasons. Even more important changes in the surface albedo are associated with changes in snow cover and sea ice, which also influence the latent and sensible heat fluxes between the atmosphere and the surface. These components are frequently regarded as indicators of climate changes on both seasonal and longer time scales, but as noted above, they are also potentially important factors in forcing change in climate. Consequently, they are covered in more detail in Chapter 8.

Improved understanding of the physical processes that determine the amount and spatial distribution of precipitation is recognized by the committee and in other studies (*Atmospheric Precipitation: Prediction and Research Problems*, National Academy Press, 1980) as one of the fundamental problems of meteorology. The physics of precipitation involves atmospheric structure, dynamics, and thermodynamics ranging over scales from 10^{-6} m to 10^{7} m. The interaction of processes on these scales must be determined from integrated observational and theoretical studies. On the large end of the spatial-scale spectrum, satellite observations of atmospheric water vapor and surface characteristics are necessary for understanding and predicting precipitation.

Item 5

Cloud characteristics including type, amount, height, temperature, liquid water content, and radiative properties.

Clouds play such a fundamental role in the radiation budget of the atmosphere that definitive climate studies will not be possible until this role of clouds is incorporated more realistically in numerical models. To do so requires further observations from space. In addition, clouds provide an obstacle to the use of infrared sensors in space to detect conditions below the clouds. Further advances in exploiting infrared techniques will therefore require improved treatment of cloud properties. More detail is given in Chapter 8.

Clouds are also important in many ways for mesoscale weather systems. The evolution of convective clouds and their interaction with their environment is one of the central problems of mesoscale meteorology. A second major problem is precipitation and the processes that determine its spatial and temporal distribution. Even thin layers of nonprecipitating clouds affect many mesoscale phenomena through their effect on the surface energy budget. High-resolution measurements of all types of clouds are therefore an essential component of mesoscale studies.

Item 6

Surface radiation and albedo; radiation at the top of the atmosphere.

Closely related to space-based techniques used to measure surface temperature are those used to compute incoming shortwave radiation at the sea surface. It also seems possible to determine outgoing surface radiative fluxes with algorithms based on currently available satellite infrared and visible data. Accuracy required is 10 W/m^2 over 100 km. Surface albedo is required to an accuracy of ± 0.02 over 100 km with a sampling frequency of once every 5 days for large-scale studies. For mesoscale studies, a higher sampling frequency of once per day is desirable. These stated temporal and spatial resolutions are in general the maximum required; lower resolutions may be applicable depending on the degree of spatial homogeneity and temporal invariance exhibited by the surface.

To determine the heat balance of the atmosphere and the climate system as a whole, it is essential to measure the absorbed solar radiation and outgoing longwave radiation on a continuing basis. The radiation budget measurements can also be used to infer the role of clouds in the radiative budget of the climate system. Accuracy desired is 10 W/m^2 over 100 km every 5 days. However, because of the strong diurnal variation in the solar radiation, the measurements should be made every 3 hours or so to get the desired accuracy of 10 W/m^2. (See also Chapter 8.)

ADVANCES IN THEORY AND DATA ANALYSIS

The atmosphere, perhaps more than any other medium in the earth system, has proven amenable to theoretical analysis and modeling.

We now possess elaborate models of the global atmosphere and the computers capable of integrating these models over meaningful time scales. The committee emphasizes that these models have played and will play an important role in understanding and predicting tropospheric weather and climate. *The committee recommends that models be developed or further improved in order to increase our understanding of weather and climate and to improve predictions.*

The term "models" is used here in a general sense. It includes not only the deterministic numerical weather prediction and atmospheric general circulation models based upon the governing physical laws of motion and thermodynamics, but also models that may be entirely statistical in origin. For mesoscale predictions on all time scales and extended-range, large-scale predictions, it is necessary to recognize the stochastic nature of the atmosphere and that elements of each approach are needed.

The development of models ranging over varying scales and degrees of complexity requires development of parameterizations of processes that cannot be explicitly included (parameterization in this context refers to the process whereby the net effect of scales of motion unresolved by a model upon those scales that are resolved is represented through use of simplified relationships between the scales.) For the large-scale models, parameterizations are required for the effects of mesoscale motions such as moist convective systems, frontal zones, internal gravity waves, clouds, radiative transfer, and turbulent transfers of heat, momentum, and moisture. The main factors involved in improving model short- and medium-range forecasts appear to be the accuracy and coverage of atmospheric observations, the initialization of the model, the horizontal and vertical resolution of the model, parameterization of convection and boundary layer processes, and the accurate specification of surface temperatures, cloud cover, and hydrology.

Observations on all scales are necessary to develop parameterizations and validate the models, and the models themselves are necessary to interpret and evaluate the observations.

In addition, the models can be used for sensitivity studies and to investigate the predictability of the atmosphere and climate system. Thus, modeling experiments may be designed to address specifically the first goal of understanding the overall system by (1) holding all boundary conditions fixed in order to evaluate internal atmospheric processes, (2) specifying changes in the boundary conditions to determine the response of the atmosphere, (3) specifying the atmospheric evolution in order to evaluate the response of the oceans, cryosphere, biosphere, and land surface, and ultimately (4) determining the response of the entire coupled system.

Optimal use of observing systems in the future will also demand not only ongoing development of new instrumentation and means of acquiring the needed data, but also the development of efficient data processing schemes to extract the information required, along with methods to consolidate and assimilate all types of data. *The committee concludes that it will be necessary to evaluate the effectiveness of current observing systems and design optimum future systems capable of providing the needed data base.*

ADVANCES IN INSTRUMENTATION

It is clear from this discussion of scientific objectives for the troposphere that a number of advances in instrumentation are needed to accomplish them. In some cases, these advances consist of improvements in the quality of the measurements being obtained with operational techniques. In other cases, new instrumentation will need to be developed. Those areas in which advances in instrumentation are particularly called for are (1) surface winds and stress, probably by means of a scatterometer, (2) precipitation, probably by means of both active and passive microwave systems, (3) wind in the free atmosphere, perhaps by means of a Doppler lidar, and (4) sea level pressure, perhaps by means of a microwave pressure sounder. In several instances, what is called for is not necessarily new instrumentation, but rather the development of improved algorithms to infer quantities from current instrumentation. For example, measurements of precipitation may benefit from not only new technology, but also advances in algorithm development. Improvements in algorithms (perhaps with new instrumentation) are needed to produce advances in measurement capability in the following areas: (1) soil moisture, (2) surface temperatures, (3) fluxes of latent and sensible heat, (4) sea surface temperatures, (5) surface radiation, and (6) vegetative cover. *The committee recommends a vigorous program be pursued to develop instruments and algorithms to make measurements necessary to achieve the stated objectives for the troposphere.*

5
Goals and Objectives for the Stratosphere and Mesosphere

INTRODUCTION

The stratosphere extends from the cold tropopause at an altitude of 6 to 16 km, to the warm stratopause at an altitude around 50 km. Above 50-km altitude lies the mesosphere, which extends to the mesopause, a very cold layer at 80-km altitude. These two regions are commonly referred to collectively as the middle atmosphere, and they contain about 15 percent of the atmospheric mass. They are similar to the lower atmosphere (troposphere), in that the molecules are electrically neutral, and well mixed. Unlike the lower atmosphere, however, photochemical processes are closely linked to the dynamics in the middle atmosphere. Water vapor condensation is important only near the tropical tropopause, and the major motions are characterized by relatively large horizontal scales.

The middle atmosphere, although distant and tenuous, is of vital importance to man. The crucial role played by the stratospheric ozone layer in shielding the Earth's surface from biologically damaging ultraviolet radiation makes the study of its chemistry of direct relevance to life on Earth—past, present, and future. The abundance of ozone is maintained by a number of interrelated chemical and dynamical processes. Certain large-scale human activities, including industrial emissions of various chemical compounds, aircraft exhaust emissions, and agricultural use of fertilizers, result in the direct or indirect injection into the stratosphere of reactive compounds of chlorine and nitrogen. Even at concentrations of a few parts per billion by volume (ppbv) or less, these reactive compounds can catalytically destroy stratospheric ozone and alter its spatial distribution.

On the average, a 1 percent reduction in total ozone results in a 2 percent increase at the Earth's surface in the intensity of ultraviolet radiation at wavelengths capable of damaging DNA molecules. Such an increase would be detrimental for many forms of life both on the land and in the oceans. Most attention has focused on the probable increased incidence of skin cancers in humans, but grazing animals and field crops could also be affected by increases in ultraviolet irradiation.

A recent report (*Causes and Effects of Changes in Stratospheric Ozone: Update 1983*, National Academy Press, 1984) discusses the currently predicted effects of chlorine, nitrogen, and other compounds on the ozone layer and the influences of increased ultraviolet dosages on living organisms. Another recent report (*The Stratosphere, 1981: Theory and Measurements*, World Meteorological Organization, 1982) provides an extensive review of our current knowledge of the composition, chemistry, and circulation of the stratosphere and a detailed consideration of stratospheric models and their accuracy both in describing the observed stratosphere and as prognostic tools.

The middle atmosphere also has an important influence on climate at the Earth's surface. Stratospheric aerosols, for example, play a nonnegligible role in the global energy budget. The majority of them appear to be derived from sulfur gases (SO_2 and COS) transported up from the troposphere, although the stratospheric sulfur cycle is poorly understood. Volcanic eruptions, such as those of Mt. Agung or the recent El Chichon event, provide episodic injections into the stratosphere of sulfur gases and dust that can lead to significant increases of several years' duration in stratospheric aerosols.

In addition, radiative exchange with ozone and other infrared active gases in the stratosphere affects the heat budget of the surface. Long-term changes in these factors could alter the surface energy budget, especially in high latitudes, and lead to small but important changes in tropospheric temperature gradients and thus tropospheric dynamics.

In addition to these roles, the middle atmosphere interacts with the dynamics of the troposphere, influencing the motions taking place there and affecting the development of weather. In particular, thermal and orographic forcing patterns of the lower troposphere produce planetary-scale waves that propagate into the stratosphere. On some occasions, these waves are reflected back down into the lower atmosphere, where they may interfere with tropospheric waves, resulting in persistent patterns that modify the weather for considerable periods of time.

There has been a steady growth of understanding of the chemistry, dynamics, and radiation in the middle atmosphere in the last decade because of scientific and societal interest in the chemical stability of the ozone layer. Three recent developments offer promise of providing further progress in understanding over the next few years.

The first of these developments is the refinement of methods for making in-situ stratospheric measurements, especially from balloons but also from aircraft. The first in-situ techniques were capable of measuring only a few of the long-lived species. It now appears possible to make repeated measurements of the vertical profiles of the long-lived species as well as of the highly reactive radicals that are present in extremely small concentrations and possess very short lifetimes. Simultaneous measurements of several interacting species are expected to make a major impact on our understanding of stratospheric chemistry, even if they are made at only a very few locations, and even though they do not address directly the question of the effects of atmospheric motions.

The second development is the emergence of satellite-borne observations as a major tool for middle atmospheric research on a global scale. With the flight of the first remote temperature sounders on Nimbus-3 in 1969, it became possible to obtain data on the global atmosphere up to 30-km altitude. Instruments on subsequent Nimbus satellites have made observations to 80 km, attained much greater vertical resolution, and have been able also to measure a number of the chemically important trace species in the middle atmosphere (see Figure 5.1). These data complement the balloon-borne observations, for although to date they have measured fewer interacting species, they are directly applicable to studying the interactions of chemistry and dynamics.

The third development is the considerable recent improvement in models of middle atmosphere behavior. Most of the initial studies of ozone chemistry were carried out with one-dimensional models, embodying extremely simplified dynamics but capable of very complex chemistry. These allowed a detailed exploration of purely chemical questions, but the results provided, at best, a description of the global average. Conversely, a few three-dimensional circulation models existed that allowed more detailed dynamical calculations, but had minimal, or no, chemistry. Now models exist in which two- or three-dimensional dynamical calculations are carried out with detailed

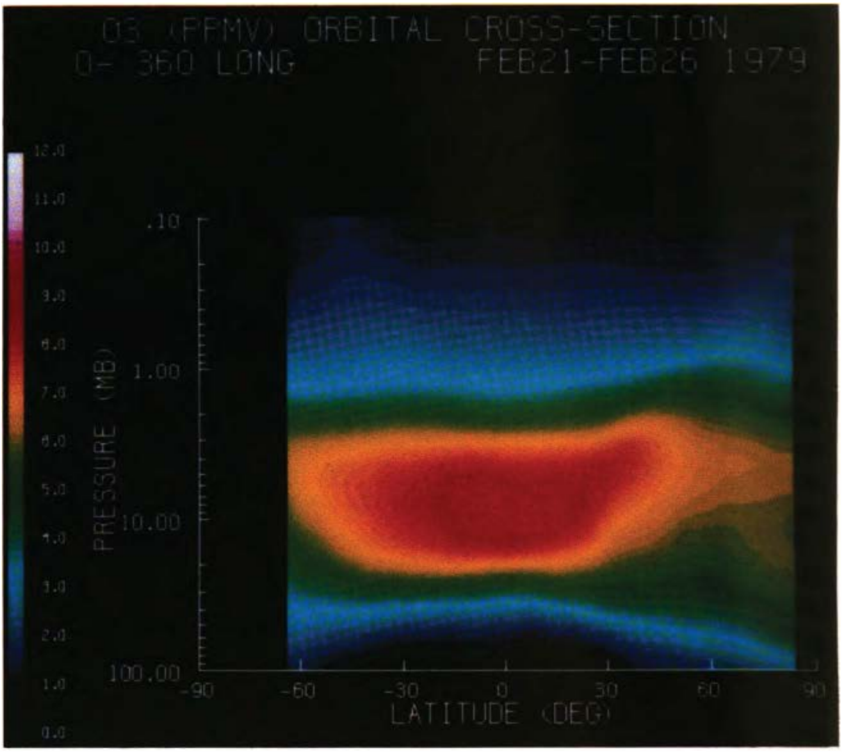


FIGURE 5.1 Zonal-mean ozone cross-section measured by the Limb Infrared Monitor of the Stratosphere on Nimbus-7.

chemistry. These middle atmospheric models, like the models developed for the lower atmosphere, are important tools for theoretical understanding and prediction. A related development is the emergence of new theoretical approaches to stratospheric dynamics based on the Lagrangian (in contrast to the Eulerian) formulation of the fluid dynamical equations. These models have already proven useful in improving the physical picture of stratospheric phenomena such as sudden warmings.

With these new research tools in hand, answers to some of the outstanding questions of the middle atmosphere can at last be obtained. A brief review of some of these problems follows.

Ozone Chemistry

As noted earlier, ozone is important because it prevents biologically dangerous ultraviolet solar radiation from reaching the surface. Ozone was known to be a constituent of the Earth's atmosphere in the nineteenth century, but the chemical theory of its presence, based only on forms of oxygen, was not put forward until the 1930's. By the late 1960's it was clear that this scheme led to an overprediction of stratospheric ozone. Catalytic destruction of ozone by photolytic fragments of H_2O was proposed but found to be insufficient to explain ozone levels in the stratosphere, although these fragments play a major chemical role in the mesosphere. Then catalytic destruction of ozone by nitrogen compounds was proposed as the natural process controlling the stratospheric ozone abundance. Concern was therefore expressed in the early 1970's that large fleets of supersonic transports injecting additional amounts of nitric oxide into the lower stratosphere could lead to significant reductions in ozone amounts. Later studies, based on a better knowledge of the chemistry involved, indicated much smaller reductions.

For economic and other reasons, large supersonic transport fleets did not come into being. However, new concerns developed when the catalytic efficiency of chlorine compounds for ozone destruction was pointed out in the mid-1970's. Chlorine is released in the stratosphere by the photolysis of the chlorofluorocarbons CF_2Cl_2 and $CFCl_3$, which are being released into the atmosphere from spray cans, refrigeration devices, and some industrial processes. A small but similar role for bromine compounds has been suggested.

The major theoretical progress since these initial discoveries has resulted from the incorporation of improved reaction rates, and the recognition of temporary reservoir species such as chlorine nitrate that lead to a strong connection between families of reactants. Accompanying these theoretical advances were a significant number of observations from balloons and aircraft that provided at least qualitative support for the theory. It is now very clear that stratospheric ozone concentrations, which are typically of the order of several parts per million, can be controlled by gases present in only a few parts per billion.

While considerable progress has been made in recent years in our knowledge of the chemistry of the middle atmosphere and of the ozone layer in particular, many outstanding problems remain. For example, there are important disagreements between models and observations for the species ClO, CH_4, and NO_2 that directly affect the question of the validity of these models for prognostic purposes. There is an insufficient record of the trend, if any, in the total column amount of global ozone over the past few decades to adequately differentiate between natural and anthropogenic influences. There is a lack of stratospheric measurements of important species such as CH_3CCl_3, $ClONO_2$, N_2O_5, and HO_2NO_2, some of which have not been observed at all. Observations of the photochemically ubiquitous radicals OH and HO_2 are insufficient to define their latitudinal, diurnal, and seasonal variations, and no direct measurements exist in the lower part of the ozone layer itself (15- to 30-km altitudes).

Sudden Stratospheric Warmings

These are the most impressive of the middle-atmospheric meteorological phenomena. The temperature in large regions in the high-latitude winter stratosphere may warm by 70C or more in a few days, accompanied by temperature decreases in the high-latitude mesosphere. Simultaneously, small stratospheric coolings in the tropics and small warmings in the tropical mesosphere are observed. Accompanying the warming, the high-latitude zonal wind reverses; a region of westward wind extends down to altitudes of about 30 km and from the pole to 60 latitude. Additionally, during these periods large transports of trace gases can take place.

Recently, there has been considerable progress in explaining how stratospheric warmings occur. Waves in the troposphere with large meridional and longitudinal wavelengths can propagate into the stratosphere. Recent work based on understanding the behavior of individual air masses (i.e., a Lagrangian theory) has provided a clearer picture of the ways in which the wave transports of heat and momentum cause the zonal wind to decelerate or even reverse, thereby inducing a meridional circulation that brings about the observed patterns of heating and cooling by nearly adiabatic processes.

There are, however, many areas of uncertainty, including the explanation of the initiation and maintenance of the waves, their interactions with each other as well as with the zonal flow, the role of traveling waves, and the mechanisms by which they are guided into the polar cap region. Indeed, it has been argued that the initiation of warmings is a local event, and that a picture in terms of zonal waves is not physically meaningful. There are also many questions concerning the roles of resonance phenomena and the lines at which the zonal wind speed is exactly equal to the wave phase speed at the onset of warmings.

Radiative-Chemical-Dynamical Feedbacks

A characteristic of the middle atmosphere is the strong coupling among radiative, chemical, and dynamical processes. Solar ultraviolet radiation is responsible for producing trace species such as ozone. The ozone absorbs solar radiation, as well as absorbing and emitting infrared radiation, and thus affects the pattern of diabatic heating and cooling of the atmosphere. This, in turn, affects both the circulation and the temperature. The temperature changes affect the reactive trace species through the temperature dependence of many of the reaction rates, and the circulation changes affect the transport of these reactive species. Circulation changes, by changing the overburdens of absorbing gases, also modify the amount of active radiation reaching a level, and hence affect the rate of photochemical processes. A particularly interesting question addresses the rate at which radiative and chemical effects damp out upward propagating planetary waves.

While models based on laboratory data predict these effects, there has been very little verification of the mechanisms in the atmosphere. These processes are crucial, so there can be little confidence in models until the effects have been qualitatively and quantitatively verified.

The Role of Transport in Maintaining the Mean Distribution of Trace Species

Photochemical processes lead to the production and destruction of numerous trace species in the stratosphere. In the absence of motions, the distribution of these species could be calculated by assuming a photochemical steady state. This is also the limiting case when the characteristic time for the photochemical processes is much shorter than the time for dynamical processes to change the local concentration. In the more general case, dynamical processes will be important in modifying this distribution, transporting trace molecules from regions in which they are created to regions in which they are destroyed. Ozone provides a good example of these processes. The maximum rate of formation occurs in the tropical upper stratosphere, but the largest densities are found in the high-latitude lower stratosphere as a result of transports.

Two- and three-dimensional computer models are beginning to simulate the transports with some degree of realism, but among the many unresolved questions are the effects of changing photochemistry on a moving air parcel and the importance of small-scale diffusion processes.

The mean distribution of a trace species is due to an approximate balance between transport and photochemical production and loss terms. It will require studies using observed gas distributions to tell how well our present understanding of these terms agrees with the real atmosphere. A particularly important transport is that responsible for troposphere-stratosphere exchange, bringing the initial species of the chemical groups from their tropospheric source regions into the stratosphere. Most evidence points to the predominance of the tropical injection mechanism, in which exchange takes place primarily by upward motions through the tropical tropopause, as part of the ascending branch of the Hadley cell. This mechanism has been used in particular to explain the stratospheric water vapor balance. In this case, it leaves numerous questions, including an observed minimum mixing ratio several kilometers above the tropopause, and the putative low frequency of clouds actually reaching the tropopause. There is thus considerable uncertainty in the detailed working of this critical process.

Small-Scale Processes

Airline passengers not infrequently experience turbulence in the lower stratosphere. Measurements of various types have shown that such small-scale motions occur over a large range of altitudes and latitudes. Other measurements have indicated the existence of wavelike structures, which appear to be due to propagating inertia-gravity waves. Some variations may be due to tidal motions, which have large spatial scales, but temporal scales that are shorter than those for meteorological disturbances.

The existence of these small-scale motions is well known, but attention is now being paid to their role in the large-scale circulation. A particular example concerns the circulation in the mesosphere, 50 to 80 km above the Earth's surface. The cold summer and warm winter mesopause regions suggest a pole-to-pole circulation in the meridional plane (with adiabatic heating at the winter pole and cooling at the summer pole). However, the Coriolis torques on the horizontal circulation should lead to large zonal velocities, which are not observed. It appears that there must be friction or drag, which balances the Coriolis force. Breaking gravity waves may provide the required balance in momentum. Propagating from the troposphere, they communicate the surface angular velocity to the atmosphere at the mesopause. There have been further suggestions that small-scale motions are important to the heat and momentum budgets in the stratosphere. If these conjectures are verified, they will cause a considerable change in the way in which the middle atmosphere is believed to work, and complicate the attempts to model its behavior in a self-consistent manner.

SCIENTIFIC GOALS

With the preceding discussion in mind, the overall scientific goals and the elements of a strategy to achieve these goals can be defined. The primary scientific goals of the study of the middle atmosphere are (1) *to understand quantitatively the radiative, chemical, and dynamical processes and their couplings, which determine the structure, circulation, and distribution of ozone and trace constituents in the middle atmosphere; and (2) to use this knowledge as the basis for understanding observed changes in the ozone distribution, and for predicting the impact of anthropogenic chemical perturbations of the middle atmosphere on the ozone layer and on the meteorology and climatology of the troposphere.*

The goals incorporate the concept of obtaining detailed measurements of all possible interacting elements of the system for a limited period, to check the understanding of the basic processes. Subsequently, through measurement of the key causal factors, it will be possible to determine the reasons for any observed change in ozone or aerosol opacity.

SCIENTIFIC OBJECTIVES

The primary scientific objectives for the study of the middle atmosphere from space for the next 10 to 15 years are, in order of priority:

1. *(a) To measure continuously total ozone and its vertical profile over the globe with sufficient accuracy to test theoretical predictions. (b) To measure simultaneously the vertical profiles of atoms and radicals involved in ozone chemistry and the source and sink species of these atoms and radicals, as a function of latitude and time of year.*
2. *To measure the vertical, horizontal, and temporal variation of temperature over the globe, and of winds in low latitudes and in the mesosphere, for at least two solar cycles.*
3. *To measure long-term variations in key variables affecting ozone and sulfate aerosol in the stratosphere, including (a) critical species*

of reactive chlorine, nitrogen, hydrogen, and sulfur, and (b) the spectrum of solar radiation from 120 to 310 nm.

4. *To measure temperature, major trace constituents, and energetic emissions in the mesopause region and lower thermosphere.*

These observational objectives are very broad. The strategy for achieving them must involve global as well as local measurements. Thus there are important roles to be played by earth-orbiting, balloon-borne, airborne, ground-based and laboratory observing systems. The scientific rationale and measurement requirements for each of the objectives are given below.

Objective 1(a)

To measure continuously total ozone and its vertical profile over the globe with sufficient accuracy to test theoretical predictions.

Ozone is at the center of many of the present societal concerns about the middle atmosphere. Continuous global measurements of ozone will provide a direct and necessary test of current theories of its response to natural and anthropogenic forcing. It is essential that measurements be obtained over at least the next two solar cycles. This will require particular attention to long-term stability in instrument calibration and/or intercalibration in order to ensure the required accuracy in trend measurement. In order to determine how ozone responds to solar variations, it will be necessary to achieve objective 3(b); similarly, to understand the chemistry of ozone, objective 1(b) is required, and an assessment of its interactions with the dynamics needs the results of objective 2. It is particularly desirable that objectives 1(a), 1(b), 2, and 3(b) be achieved simultaneously if data of optimum utility are to be obtained.

MEASUREMENT REQUIREMENTS. Previous measurements of total ozone have been made and provide a useful starting point for future attempts to determine trends in this variable. They have highlighted the difficulties in preventing or accurately correcting for long-term drift. The attainment of long-term stability through in-flight calibration and/or intercalibration will be necessary. An accuracy of about 10 matm-cm is sufficient, but a precision of 5 matm-cm is necessary for trend determination.

Ozone profile measurements have also been made, with vertical resolution ranging from about 1 to 10 km. The highest resolution is obtained from visible occultation measurements, and thus limited geographical coverage. Infrared limb scanning measurements have a resolution of about 3.5 km, believed to be adequate for most applications, but the duration of present data is limited to approximately 14 months. The longest series of data comes from instruments measuring backscattered ultraviolet radiation. They have a resolution of about 10 km and provide most information above 30 km, where the ozone is close to photochemical equilibrium. These data thus may not be particularly suitable for studies of ozone transport.

To be useful, profile measurements should be accurate to 10 percent or better, and precise to half of that. Further details on measurement requirements are provided in Table 5.1.

Objective 1(b)

To measure simultaneously the vertical profiles of the atoms and radicals involved in ozone chemistry and the source and sink species of these atoms and radicals, as a function of latitude and time of year.

The complexity and feedbacks in the chemistry require a range of approaches.

MEASUREMENT REQUIREMENTS. Discussion of the measurement requirements is clarified by noting that the important gases can be grouped into families of components of the elements oxygen, nitrogen, hydrogen, sulfur, and carbon. These families enter the stratosphere as relatively inert source species; there they are converted by chemical or photolytic processes into highly reactive radical species, which are involved in the catalytic chains destroying ozone. The chains are terminated by reactions converting the radicals into sink molecules, which are much less reactive, and are the primary form in which the family is removed from the stratosphere. In addition, the catalytic chains may be temporarily terminated by temporary reservoirs, which often link two families and are of low reactivity.

Thus, the gases of interest are as follows:

Source molecules: $CFCl_3$, CF_2Cl_2, CH_3CCl_3, CCl_4, CH_3Cl, $CHClF_2$, N_2O, H_2O, CH_4, OCS, SO_2, and CO
Radicals: Cl, ClO, NO, NO_2, OH, HO_2, and HSO_3
Sink molecules: HCl, HNO_3, (H_2O), and H_2SO_4
Temporary reservoirs: $ClONO_2$, HOCl, NO_3, HONO, HO_2NO_2, and N_2O_5

It is necessary to know at least the zonal-mean distribution of the source and sink species as a function of time. The distributions of these species depend on both chemistry and transport. For use as tracers of atmospheric motions, it would be desirable to have measurements of the mean distributions and the spatial and temporal variations of each gas that takes part in the chemistry of the middle atmosphere. However, the differing distributions of trace species are strongly influenced by their differing photochemical lifetimes and distributions of sources and sinks. The requirement is to obtain measurements of the distributions of a set of gases that span the range of lifetimes from several hours to several weeks or months, which includes both those having tropospheric and those having stratospheric sources. At the extremes, species with very short lifetimes (minutes or less) will not be much affected by transports (which typically have time scales of days or weeks), whereas species with very long lifetimes (100 years or longer) will approach uniform mixing in the atmosphere, unless large emissions into (or removal from) the atmosphere are occurring.

In order to provide a quantitative demonstration of the catalytic cycles affecting ozone, simultaneous measurements of the vertical profiles of ozone and at least one radical from each family are required. The relevant catalytic cycles have time scales of minutes or less, and thus the relative concentrations of these reactive species are usually determined by chemistry, not transport.

Simultaneous measurements of these reactive species are required as functions of solar zenith angle to study the detailed workings of the chemical cycles, but need only be made for a limited number of seasonal and geographical situations. Balloon platforms are well suited to obtaining these measurements with in-situ instruments. When the chemistry is well established through such measurements, it then will be possible to calculate the concentrations of several of the radicals solely from measurements of radicals and species that are potentially or actually measurable from space (e.g., ClO, NO, and NO_2).

Measurements are also required for the temporary reservoirs. Until appropriate remote-sensing techniques are developed, balloon-borne measurements are probably more appropriate than attempts to measure these species from space.

While the relative concentrations of reactive species are often determined by chemistry alone, the absolute concentrations of some reactive species, or families of reactive species, are determined both by transport and by chemistry. For these longer-lived species, or families of species (e.g., NO_2 + NO, and OH + HO_2), the required measurements are similar to those for source and sink species discussed above if the measurements can be made from space.

The requirements for measurements from space (see Table 5.1) are similar for all species: latitudinal-longitudinal resolution of 5° × 15°, vertical resolution about 3.5 km, an accuracy of better than 20 percent and a precision of better than 10 percent. Much greater vertical resolution can be obtained by balloons but with very little spatial and temporal coverage. Wherever possible, balloon-borne measurements of common and complementary species (with higher vertical resolution) should be obtained during satellite overpasses to provide additional insight into the chemistry.

Objective 2

To measure the vertical, horizontal, and temporal variation of temperature over the globe, and of winds in low latitudes and in the mesosphere.

In order to understand the middle atmosphere, a more complete picture must be developed of the large-scale circulation and transports of the middle atmosphere, and the mechanisms responsible for maintaining them. Large-scale refers to characteristic length scales of 1000 km or greater.

The large-scale circulation includes the time mean distributions of temperature, height of pressure surfaces, wave amplitudes, wave phases, zonal wind, and mean meridional circulation, averaged over convenient periods of time (e.g., 1 month). It also includes, among other derived quantities, the mean transports of heat, angular momentum, and energy.

The large planetary waves are the most obvious features in midlatitudes. They are able to transport potential vorticity from one region to another, thereby accelerating or decelerating the zonal wind. This appears to be essential to the sudden warming phenomenon discussed earlier. Accompanying the changes in the zonal wind is a secondary circulation in the meridional plane.

There are many questions concerning waves in the upper atmosphere. Stationary waves in the atmosphere are believed to be mainly due to forcing by orography and differential heating, but the excitation of traveling waves in the stratosphere is not understood at this time. Linear theory has often been used to explain the structure and propagation of planetary waves, but given the restrictive assumptions generally made, the extent to which such theory is valid remains to be determined. In this regard, recent evidence indicates that wave-wave interactions frequently may be important. It is not clear whether wave reflection or resonance phenomena are important for wave growth in the atmosphere. Finally, it is desirable to know what the necessary and sufficient conditions are for the initiation of stratospheric warmings, and the extent to which they are predictable.

It is also necessary to be able to sort out the extent to which the large wave amplitudes in the middle atmosphere are due to a flux of mechanical energy from below, and the extent to which they result from amplification in the middle atmosphere. For the troposphere, the importance of this question lies in the extent to which these waves interact with their source regions and influence tropospheric weather.

Suitable observations will also allow testing of the suggestion that there are, at least occasionally, regions of baroclinic and barotropic instability in the middle atmosphere, and determination of their importance to the general circulation. Similarly, suggestions that solar events and storms in the magnetosphere can affect motions in the upper mesosphere can be checked.

Knowledge of the circulation is essential to the understanding of distributions of trace species. As noted earlier, the average distributions of long-lived trace species are maintained by an approximate balance between photochemical and transport effects. The transports create a photochemical nonsteady state, so that slightly more of a trace gas is produced than destroyed in one region, while the opposite takes place in another. Sufficient knowledge of both the transport and the photochemistry is required for the resulting calculated distribution to agree with that observed. The interplay between theory and observation is essential for the creation and validation of global models with which to investigate the sensitivity of the middle atmosphere, and especially its chemistry, to anthropogenic perturbations, and its influence on tropospheric climate.

MEASUREMENT REQUIREMENTS. For most of the region below 1 mbar, the winds are close to being geostrophic; that is, the Coriolis force is approximately balanced by the pressure gradient force. Knowledge of the pressure and temperature fields permits the geostrophic wind to be calculated. Scale analysis indicates that the geostrophic wind velocity should be within about 10 percent or less of the true wind velocity, at least up to the stratopause. This appears to be borne out by preliminary calculations based on Nimbus-7 data.

To support the objectives in middle atmospheric dynamics and transports, the principal requirement is for measurements of the global temperature distribution from 10 to 80 km or higher, over at least a solar cycle, in order for interannual variability to be observed, and to be able to identify and measure trends.

To be useful, such data must be able to be related so that true trends can be separated from instrumental effects. The temperature should be accurate to 1°C everywhere, with a precision of 0.5 K at lower levels. The accuracy may degrade to 3°C at 80 km and 10°C at 120

TABLE 5.1 Measurement Requirements for Stratospheric and Mesospheric Research

Objective	Measurement	Accuracy	Precision	Vertical Resolution	Horizontal Resolution, Latitude × Longitude
1(a)	Total ozone	10 matm-cm	5 matm-cm	—	5° × 10°
	Ozone profile	10%	5%	3.5 km	5° x 10°
1(b)	Source molecules	<20%	<10%	3.5 km[a]	5° x 15°
	Sink molecules	<20%	<10%	3.5 km	5° x 15°
	Radicals	<20%	<10%	3.5 km	5° x 15°
	Temporary reservoir species	<20%	<10%	3.5 km	5° x 15°
2	Temperature	<1 K	<0.5 K	3.5 km	5° x 15°
	Wind	<2 m/s	<2 m/s	3.5 km	5° x 15°
3(a)	Critical molecules	<20%	<10%	3.5 km	5° x zonal mean
	Aerosol layer optical thickness	<20%	<10%	3.5 km	5° x zonal mean
3(b)	Solar UV irradiance	10%	0.1% short term[b] 2% long term[b]	(wavelength resolution = 1 nm)	
4	Thermospheric temperature	2 K	3-10 K	3.5 km	5° x 15°
	Trace constituents	25%	25%	3.5 km	5° x 15°
	Emission features	25%	25%	3.5 km	50 km x 50 km

[a] Better vertical resolution needed at the tropopause.
[b] Wavelength dependent. Values shown apply at 200 nm.

km. The observing system should be capable of resolving wavelike disturbances in the vertical having amplitudes of 2°C and perturbations of 4-km vertical size in the stratosphere. Horizontal sampling should be 5 latitude by 15 longitude.

The temperature is also a vitally important variable for atmospheric thermodynamics, energetics, and chemistry, and needs to be measured for those reasons as well.

Direct measurements of wind are needed to provide information on the ageostrophic component of the wind. The latter is expected to be large above 50 km, and also in the tropics where geostrophic wind calculations become very sensitive to errors in the pressure field.

Winds should have an accuracy of ±2 m/s below 1 mbar, and ±5 m/s below 80 km. For compatibility, these should have a spatial resolution similar to that of the temperatures. These various measurement requirements are summarized in Table 5.1.

Objective 3

To measure long-term variations in key variables affecting ozone and sulfate aerosol in the stratosphere including (a) critical species of reactive chlorine, nitrogen, hydrogen, and sulfur, and (b) the spectrum of solar radiation from 120 to 310 mm.

In addition to understanding the physical and chemical processes that control the present composition of the middle atmosphere (objectives 1(b), 2, and 3(b)), it is also necessary to observe and understand any long-term changes that are taking place. Thus, if there are changes in the ozone concentration (objective 1 (a)), these need to be compared to changes that are expected based on changes in temperature (objective 2), changes in stratospheric composition, including how the concentrations of the various sources of reactive radicals are changing (objective 3 (a)) and changes in the solar ultraviolet output (objective 3(b)).

MEASUREMENT REQUIREMENTS. This objective requires long-term measurements of at least a subset of key species involved in ozone chemistry. Ideally, this includes some of the radical species active in the catalytic destruction cycles. In addition, stratospheric trends of the major source gases are needed. Some of these have natural sources, but many have anthropogenic origins. Some source gases are more conveniently measured at the surface, but it is necessary to measure some in the stratosphere as indicators of troposphere-stratosphere exchange. Where convenient, observations of sink species are also desirable. In addition, trends in stratospheric H_2O must be determined.

Similarly, it is necessary not only to understand the processes maintaining the aerosol layer, but to be aware of the changes in precursors that may lead to changes in the concentration of particles and optical depth of the layer. Thus it will be necessary to determine the sources and trends in the precursor gases OCS and SO_2, and also trends in the thickness of the aerosol layer.

Trends in trace gases that are radiatively active and have an effect on the radiative balance of the surface and lower atmosphere must also be determined. Some of these, such as O_3 and NO_2, are primarily present in the stratosphere, and must be measured there. Others are primarily present in the troposphere, but either their concentration or their effects may be more easily measured in the middle atmosphere. Care must be taken to measure them at levels where their concentration is not strongly modified by photochemical processes.

Carbon dioxide (CO_2) is a special case. It seems likely that its concentration in the middle atmosphere can be measured from space by occultation. From the measured concentration and CO_2 radiance signal, the middle atmosphere temperature can be derived and examined for evidence of a middle atmosphere temperature decrease. Calculations suggest this will accompany the surface temperature increase caused by the CO_2 greenhouse effect.

Stratospheric water vapor should be a very sensitive indicator of temperature at the tropical tropopause. The greenhouse gases CH_4 and N_2O are remotely measured more easily in the stratosphere than in the troposphere, as are $CFCl_3$ and CF_2Cl_2. These radiatively active gases are discussed further in Chapter 8.

Global measurements of these gases over an extended period are needed with sufficient accuracy to define their long-term trends. Requirements on horizontal resolution are not demanding: zonal means with 5 latitudinal spacing are sufficient. Vertical resolution should be about 3.5 km for gases, which vary rapidly with altitude. Accuracies of 20 percent and precisions of 10 percent are adequate, but the primary concern is long-term reliability of the calibrations of the measurements. Long-term drift of the calibration and differences among instruments used over the period must be minimized.

The large uncertainty in our knowledge of the absolute spectral irradiance of the sun in the ultraviolet precludes accurate modeling of the middle atmosphere, especially in regions dominated by photochemistry. This arises because the ultraviolet irradiance controls not only the composition but also the temperature. The irradiance also varies with the 27-day rotation period and the solar cycle, and it is important to determine this variation as a function of wavelength, since many quantities are predicted to vary in response to such changes. Measuring both the solar drive and the atmospheric response will permit sensitive tests of theory. In addition, since there are large uncertainties in the opacity of the atmosphere in the 180- to 240-nm region, intensity measurements as a function of altitude are also required to define and test opacity models.

The ultraviolet intensity measurements are required with an accuracy of about 10 percent, with special precautions against long-term drift in the calibration for observations of solar variations. A precision of about 1 percent is needed for good resolution of the solar cycle oscillations at 200 nm, which are believed to have an amplitude of 5 to 10 percent. Further details are given in Table 5.1.

Objective 4

To measure temperature, major trace constituents, and emission features in the mesopause region and lower thermosphere.

The mesopause is an extremely interesting and important boundary in the atmosphere. The region below is largely dominated by motions propagating up from the troposphere, the major constituents are uniformly mixed, and the radiating levels are largely in local thermodynamic equilibrium (LTE), i.e., the radiating levels are populated according to a Boltzmann distribution. In the overlying region, solar effects drive short-term motions, each constituent diffuses vertically according to its own molecular weight, and radiating levels are not in LTE. In addition, high-frequency motions, such as gravity waves and tides, are a major part of the motion system.

There are many important questions about these high layers. What role do the small-scale motions play in the large-scale circulation in this region? How much do non-LTE effects change the atmospheric cooling at the mesopause, and thus affect the meridional circulation? How do radiative emissions by CO_2 act to get rid of energy deposited in this region by auroral and solar events? What combination of chemistry and motions is responsible for the winter anomalies in the D region of the ionosphere? To what extent does auroral NO get transported into the polar night stratosphere?

The mesopause and lower thermosphere have hitherto been essentially impossible to observe in any systematic way. These regions are too low for satellite in-situ observations, yet they lie above the remote-sensing capability of atmospheric sounders because of their extremely weak emissions.

Recent improvements in instrument sensitivity now allow this region to be remotely sounded. For the first time a detailed look at the many processes taking place there can be obtained.

MEASUREMENT REQUIREMENTS. To begin to understand the mesopause and lower thermosphere, profiles of the kinetic, rotational, and vibrational temperatures of the radiatively active gases, especially CO_2, are required.

Vertical distributions of the gases NO, CO_2, H_2O, O_3, CO, and other measurable gases, with their temporal variations, are also needed, as well as direct observations of the non-LTE emissions by $O_2(^1\Delta)$) (1.27 μm, 1.56 μm), OH (1.6 to 4 μm), NO (2.8 and 5.3 μm), CO_2 (especially 2.7 and 4.3 μm), and H_2O (6.3 μm). Completion of the energy budget requires that measures of solar and auroral activity be obtained, as well as estimates of the energy spectrum of particles precipitated into this region of the atmosphere. Required accuracies are summarized in Table 5.1.

ADVANCES IN THEORY AND MODELING

A long-term research program designed to address the major scientific questions in the stratosphere and mesosphere should at any one time have sufficient focus on these outstanding questions so that progress is maximized. Nevertheless, the program should also have sufficient breadth to accommodate promising research in areas not immediately relevant to these questions and should also recognize that the definition of what is or is not an important problem may change with time.

In addition to the measurements called out by the above objectives, optimum progress will also require theoretical investigations based on a hierarchy of models. These will aid in the interpretation of stratospheric observations, provide guides to future investigations, and provide the means for making credible predictions of the response of the middle atmosphere to natural and anthropogenic perturbations. Such predictions are needed not only in a global average sense but with information on latitudinal and regional effects.

The middle atmosphere is characterized by links among radiative, chemical, and dynamical processes that require comprehensive models to account for all the important couplings. The present and future availability of high-speed computers now makes general circulation models, incorporating suitably detailed computations of chemistry and radiative transfer, a feasible objective. *The committee recommends development of general circulation models of the middle atmosphere that incorporate chemistry, radiation, and dynamics and the couplings among them*. It is clear, however, that this objective will not be fully realized for at least several years. Simplified two- and three-dimensional models already exist that can interact in a more timely and useful way with the measurement programs over the next few years. Therefore, while the ultimate objective is to produce a three-dimensional model capable of considering, simultaneously, the complicated processes involved in atmospheric chemistry, general circulation, and climate, it is important that efforts in the development and use of the more simplified models continue. *The committee emphasizes that central to the development of all models are accurate laboratory measurements of the rates of important reactions and the continued search for important "missing" reactions and species in current chemical schemes.*

Once developed, the models must demonstrate that they are capable of simulating the present state of the atmosphere, and thus presumably have incorporated the physical and chemical processes with the requisite accuracy. However, it must be emphasized that this is a necessary but not a sufficient condition for predicting long-term effects.

There are also advances required in theoretical understanding. For example, we need to determine how motions act to transport material from one region of the atmosphere to another, and how these motions are best described. One of the most obvious features of the upper atmosphere are the large-scale wave motions that may extend over 20 of latitude or more and which can transport constituents. A positive correlation between northward velocity and species concentration will result in a northward eddy transport of that species.

What is much more subtle is that the heat and momentum transports by these waves drive a circulation in the meridional plane, whose transports tend to cancel the effects of the eddy transports of trace species, heat, and momentum transports. Under the conditions of steady waves with no dissipation and no diabatic heating, there will be no net transport for a photochemically passive tracer. In general, however, these conditions are violated, and a net transport occurs. This can be visualized either as the difference between the transport by eddy and mean meridional motions (the Eulerian view) or by following the trajectories of air parcels (the Lagrangian view).

At this time it appears that there may be some advantages in developing two-dimensional models based on a quasi-Lagrangian transformed Eulerian formulation. It is not clear that there are advantages in using one approach over the other when analyzing atmospheric observations or model results.

In any case, it is necessary to demonstrate that the derived motions can be used to calculate the transports over large distances with an accuracy that will allow meaningful comparisons between model results and the real atmosphere.

While large-scale motions are responsible for the transport of trace gases over great distances, small-scale motions must ultimately be responsible for irreversibly mixing the trace substance into the new environment and preventing it from being transported back out of the region. At this time, there are only fragmentary ideas of how this diffusion takes place, its scales and physical mechanisms, and how it may best be parameterized.

ADVANCES IN INSTRUMENTATION

Observations of gravity wave characteristics appear to be most amenable to continuous observations by ground-based techniques. The mesosphere-stratosphere-troposphere (MST) radars developed in recent years have shown the capability to observe motions of small wind amplitudes and vertical sizes. Extensive analysis of these data, in conjunction with theory, will be required to demonstrate the ultimate capabilities of these systems. Similar lidar techniques can be used to augment and confirm these conclusions. The problem of determining the global distribution of gravity waves may require additional stations, but it seems more likely that newer spaceborne techniques may need to be developed.

Improvements in current techniques and/or new techniques to measure free radicals in the middle atmosphere are generally needed. For satellite-based instruments addressing NO and NO_2, we need improved precision to meet and even exceed the requirements given in Table 5.1. Remote sensing of ClO and OH in the stratosphere and mesosphere from space would add a major new dimension to our understanding of the spatial and temporal variability of the chemistry in this region. For in-situ instruments, the high-priority requirement for reliable OH measurements in the mesosphere, stratosphere, and troposphere (see Chapter 7) mandates development and implementation of a suitable technique for addressing this particular free radical. *The committee recommends coordinated development of instrumentation for accurate measurement of OH suitable for use in the lower and middle atmosphere; both in-situ and remote-sensing techniques should be considered.*

6
Goals and Objectives for the Global Hydrologic Cycle

INTRODUCTION

Water plays a central role in the world ecosystem. It is the most abundant single substance contributing to the global biomass and cycling through the biosphere. It is also a vital resource, which in many countries is extensively managed for delivery to agricultural lands. Nevertheless, less than 1 percent of the water on Earth is directly useable, and only one-half of that is easily accessible near the Earth's surface. The global supply of useable water is fragile: the global inventory of surface freshwater can be drained by the natural processes of evapotranspiration and runoff within a few years. Despite some local water surplus, many regions of the world either now or soon will experience water shortages because of inadequate quantity or quality. Future water shortages may be exacerbated by climatic change (see *Climate, Climatic Change, and Water Supply*, National Academy of Sciences, 1977).

Water in its frozen state also plays important roles in global and regional energy budgets, in weather and climate, and in the annual supply of surface water and groundwater. Snow, glaciers, including ice sheets and ice shelves, ice in seas, lakes, and rivers, and ice in the ground are the major components of the frozen part of the global system—the cryosphere. Each of these components possesses its own distinctive physical and chemical properties; seasonal and geographical variations; mechanisms of formation, movement, and loss; and interactions with the atmosphere, oceans, and land surface. Over the past

30 years our knowledge of the cryosphere has grown steadily with exploration being pursued for both scientific and economic motives. We now know that ice and snow cover play a very important interactive role in the dynamics of the Earth's climate and that, properly monitored, the world's ice volume provides a sensitive indicator of climatic change.

There are some important societal problems concerning water. Among these problems are overdraft of aquifers, water pollution, erosion and sedimentation, degradation of coastal wetlands, hazardous flooding, the chance of prolonged drought, the movement of arctic sea ice, and the occurrence of avalanches. Many of these problems involve a need for accurate prediction (see *Geophysical Predictions*, National Academy of Sciences, 1978). As society becomes increasingly more complex, interdependent, and interconnected, unlikely vicissitudes of nature can exert devastating impacts on key transportation, communication, and economic networks. The lack of long-term data on water, ice, and snow over the globe is a true impediment to progress in understanding both rare and long-acting hydrologic processes.

The global hydrologic cycle is defined here as the study of the important global reservoirs of freshwater and ice and the exchanges between these reservoirs. Whereas other sections of this report emphasize aspects of the hydrologic cycle important in tropospheric processes, climate, and the biosphere, this section will consider the understanding of this cycle principally for its own sake. The temporal and spatial scales will also be different from the atmospheric scales. Water vapor has a typical residence time of about 10 days in the lower atmosphere, but near-surface groundwater remains in place for hundreds of years and must be considered in those terms (see *The Earth and Human Affairs*, National Academy of Sciences, 1972). Global average residence times for water vary from days in rivers to decades in lakes, to centuries in glaciers. Hydrologic phenomena of interest range in spatial scale from the flows of individual streams and glaciers to regional variations in evapotranspiration and ice and snow cover, to polar-cap variations in surface albedo. Some of the outstanding problem areas in the study of the global hydrologic cycle will be reviewed below.

Water and Climate

Theoretical studies have shown that both anthropogenic change (e.g., atmospheric CO_2 increases) and natural perturbations (e.g., volcanic dust) may have significant influences on the magnitude and distribution of global precipitation and temperature. Since the latter influences evapotranspiration, then runoff (approximated as the difference between precipitation and evapotranspiration) will be highly sensitive to anticipated global climatic change. Changes in river flow and lake volumes, accelerated soil erosion, and desertification all represent significant and measurable hydrologic responses to climatic changes operating on time scales of several years to decades. These changes all lag the climatic forcing factors by differing amounts, and they occur on top of natural variations that must be understood to adequately manage their immense consequences for food productivity and other human uses of the Earth. Likewise, the global hydrologic consequences of large-scale water diversion projects, urbanization, tropical deforestation, and regional irrigation projects need to be assessed.

Hydrologic parameters have a profound influence on global atmospheric circulation and weather, as described in Chapter 4. Man-induced hydrologic influences on climate have become apparent with the advent of very large engineering projects and proposals such as drainage of the White Nile swamps, flooding of the Qattara depression, and deforestation of the Amazon. In the most spectacular example, the Soviet Union plans major alterations in the drainages of three of the world's largest rivers, the Ob, the Yenisey, and the Lena. Water that usually flows northward to the Arctic Ocean would be diverted southward to irrigate new croplands in the arid Aral-Caspian basin region. In addition to the regional effects on the impacted river regimens, this project could conceivably have a global climatic influence. Removal of freshwater from the Kara Sea might promote a system instability that would significantly change the ice cover of the Arctic Ocean. According to one scenario, the effect on northern hemisphere climate would then be major, since sea ice plays a key role in the ocean-atmosphere mass and energy exchange that dictate atmospheric pressure and circulation patterns. The fact that these putative effects cannot be predicted with certainty points to the inadequacy of our understanding of the coupled hydrologic-atmospheric system.

Water Pollution

Because water quality may be the limiting factor in water use, it is necessary to trace the sources, sinks, and movements of pollutants through rivers, lakes, the soil, groundwater, and vegetation to the atmosphere, oceans, and biosphere. For some purposes this objective can be achieved by models that relate pollution fluxes to movements of water and sediment; that is, to movements that form a part of the hydrologic cycle. For other purposes it may be necessary to develop techniques ultimately to detect pollutants directly in water by remote sensing and to monitor the chemical composition of precipitation, streamflow, and groundwater. Rates of pollutant uptake by soil, vegetation, ocean, and atmosphere could then be determined on a global basis.

The Cryosphere and Climate

We are remarkably ignorant of the cryosphere. This is due in part to the fact that in-situ studies of the arctic and antarctic regions have proven very difficult: inclement weather, ice movements ranging from a few centimeters per day to 30 km/day, rugged and time-variable ice-scapes, unpredictable openings and closings of leads, and the perpetual darkness of the polar winters have seriously inhibited ice-based and even aircraft-based studies of the polar regions. Recently, instruments on several satellites have demonstrated that observations from space can make important contributions to our knowledge of the cryosphere unhampered by many of the problems that beset in-situ studies.

Indeed, certain aspects of global snow and ice research are feasible only through observations from space. First, the remoteness and scale of the cryosphere make real-time global-scale data acquisition possible in practical terms only with satellite-borne sensors. The vastness of the cryosphere is not always appreciated: glaciers alone cover 11 percent of the Earth's land surface; over 50 percent of the land is covered (and uncovered) by snow each year; and sea ice covers 12 percent of the world's oceans. If the area where icebergs are commonly encountered is also considered, ice is observed over 22 percent of the ocean's surface. Second, many fundamental snow and ice investigations require the collection of data at regular intervals without any limitation imposed by clouds, inclement weather, or darkness; again the necessary regular observations are in most cases possible only from Earth-orbiting satellites.

Although at first glance it might appear convenient to deal with all aspects of the cryosphere simultaneously, snow, sea (and lake) ice, and ice sheets and ice shelves are quite different in their basic physics and amenability to remote sensing. It is therefore both convenient and prudent to address these three components of the cryosphere as distinct entities.

Snow not only blankets large areas of the Earth's land surface during the winter, it also commonly covers the surfaces of the large ice caps and the Earth's sea and lake ice. Its areal extent is more variable than that of any other natural material. Because snow has the highest albedo of any abundant material on the Earth's surface, its presence or absence drastically alters the surface radiation budget and therefore the surface air temperature. It also serves as a highly effective insulating layer between the Earth and the atmosphere. In addition, it causes a delay of up to several months before water released from the atmosphere actually becomes available to the land.

There are many types of snow, and changes in local weather cause changes in such snow properties as grain size and shape, hardness, density, layering, and depth. Measurable changes in such parameters within a matter of hours are not uncommon, and in many areas the snow cover characteristically shows a high degree of lateral variability. Therefore, characterizing the state of the Earth's snow cover at a given time is a difficult problem.

Just as snow modifies the albedo of the land, sea ice drastically modifies the albedo of the surface of the sea. In the "landlocked" oceans of the north, sea ice extent doubles in the winter (from 7×10^6 to 14×10^6 km^2), with the expansion largely occurring in the marginal seas of the subarctic. In the unconfined waters north of Antarctica the seasonal increase in ice extent is much larger (from 2×10^6 to 20×10^6 km^2). In addition to its effect on the albedo of the sea surface, sea ice serves as a deformable insulating layer of variable thickness in which the heat flux through cracks in the ice (leads) is up to 2 orders of magnitude greater than through the ice itself. The thicker classes of ice are produced not by growth, but by the deformation of thinner, weaker ice masses. Therefore, to understand the thermodynamics of sea ice, one must also understand its dynamics.

Sea ice modifies the Earth's seasonal temperature cycle, delaying temperature extremes through the release of its latent heat of freezing in the fall and by the uptake of heat for melting in the spring. In addition, the movement of sea ice produces a net equatorward transport of nearly fresh water and negative thermal energy at the sea surface. The growth of sea ice results in increased salinity in areas of large net ice production, as sea ice contains 70 percent less salt than the water from which it forms. Locations of particularly intense sea ice growth over shallow shelf areas appear to be sources of the cold saline water that ultimately forms the bottom water of the world's oceans. The location of the ice edge also appears to affect the path of cyclonic disturbances in the atmosphere as well as to be associated with the generation of large eddies in the ocean. Finally, the fact that sea ice by its very nature is sensitive to small changes in atmospheric and oceanic heat fluxes makes it a useful sensor of climatic change.

Lake ice problems are, in a general way, similar to sea ice problems and therefore these two ice types will be discussed together. However, as materials, lake and sea ice are very different, being low-loss and high-loss dielectrics, respectively. River ice, which couples a material with the general properties of lake ice with a set of pronounced hydrodynamic problems, will not be explicitly discussed, as it commonly occurs in water bodies that are sufficiently narrow that satellite-borne remote sensing techniques are not particularly convenient.

There is an essential difference in time scales between snow and sea (and lake) ice on the one hand and the world's largest ice sheets on the other. Snow and sea (and lake) ice can easily show measurable changes in hours and drastic changes within a week. Ice sheets and shelves, on the other hand, change much more slowly, with variations commonly measured on scales of years to tens of years and in the case of the largest ice sheets (Greenland and Antarctica), hundreds to thousands of years. Therefore it is not necessary to obtain data every day or every week on larger ice sheets, as a series of measurements separated by 1 or 2 years can be considered to be closely spaced. For many problems a repeat time of 10 to 20 years should be more than adequate to delineate significant changes.

The Earth's major ice sheets are recognized as important indicators of climate change on decadal and longer time scales. Nevertheless, our knowledge of even an apparently simple diagnostic parameter such as ice sheet volume is surprisingly poor. For instance, we do not know whether the mass of the antarctic ice sheet is currently increasing or decreasing with time. We also lack the observational base required to develop and test the physical- dynamical models of the ice sheets that are essential to prediction of long-term climatic changes.

SCIENTIFIC GOALS

In defining goals for the global hydrologic cycle, the committee recognizes the present need to improve our understanding of the relevant terrestrial systems, the hydrosphere and cryosphere, per se. The committee is also cognizant of the fact that the hydrosphere and cryosphere interact in important ways with the troposphere, biosphere, and lithosphere, and are essential to our understanding of the climate.

The first goal for the study of the global hydrologic cycle is to determine the distributions, dimensions, properties, and relevant dynamics of the major global reservoirs of freshwater substance: surface, soil, and underground water; snow, sea, and lake ice; and glacial ice sheets and shelves. This goal recognizes the need to understand these reservoirs both for their roles in the hydrologic cycle and for their roles in weather, climate, and the global energy budget.

The second goal is to determine 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, precipitation, river flow, glacial flow, melting, and freezing, which are responsible for the major fluxes in the hydrologic cycle.

The third goal is to predict on appropriate time scales the distributions, volumes, and fluxes associated with (1) land surface, soil, and underground water reservoirs; (2) snow cover; (3) sea ice; and (4) glacial ice sheets and shelves. The relevant time scales are days for soil water, weeks for land surface water and snow, weeks to years for sea ice, and years to many decades for underground water and glaciers. This goal recognizes the societal importance of the water cycle and the need to predict changes in the important reservoirs and interreservoir fluxes.

The predictability of hydrologic and cryospheric phenomena is made difficult through complex feedbacks between these phenomena, the atmospheric general circulation, and the biosphere. For example, the connections between vegetation cover, soil moisture, and rainfall are key factors in understanding the important issues of desertification and deforestation. The Amazon rain forest, for example, has a climate that is determined by extensive meteorologic recycling of moisture initiated by transpiration from the forest itself. Massive deforestation in the Amazon could lead to downwind precipitation decreases that will transform forest to savanna. The long, severe seasons of surface dryness in savanna regions feed back to the atmosphere to promote continued low precipitation. Large floods and droughts in general derive from the recurrences of certain meteorological patterns. In turn, changes in the state and output of the terrestrial hydrologic cycle influence that atmospheric circulation. It is precisely such feedback relationships that are most in need of study.

Snow and ice, surface water, underground water, and soil moisture all serve as water storage elements useful to man. They therefore constitute critical concerns in water resource management. A scientific basis for this management, which is essential to food production, can only arise from understanding the weekly, seasonal, and annual variations in water supplies that can be obtained from these sources and sinks.

Snow plays significant roles in the moisture budgets of the atmosphere and land, in the surface radiation budget, and in subsurface to surface transfers of heat. Prediction of the extent and state of the world's snow covers is therefore important in furthering our understanding of weather, regional climate, and terrestrial hydrology. Sea ice prediction is important because of the role this ice plays in determining polar (and global) albedo, in modulating the transfer of heat from the polar oceans to the atmosphere, in providing a diagnostic of long-term climate change, and in being a major hazard to many types of marine operations in the polar regions.

The growth and decay of major glaciers have been both characteristic features of and integral players in major climatic changes over the past two million years. Indeed it is now recognized that the intrinsic dynamics and thermodynamics of glaciers may have played significant roles in determining the frequency and extent of the ice ages that punctuated the Pleistocene epoch; achievement of the above goals for the Earth's glacial ice sheets and ice shelves will therefore serve to further our understanding of one of the most interesting and perplexing events in the Earth's history. It will also contribute directly to our knowledge of the stability of the major ice sheets in our present epoch.

SCIENTIFIC OBJECTIVES

Several satellite measurement objectives are necessary to meet the goal of understanding the global hydrologic cycle and its interactions with the biosphere, lithosphere, and atmosphere. These objectives, together with associated ground-based measurements, modeling, and theory, define the overall program for achieving these goals. A combination of in-situ measurements and measurements from space is definitely required. The space measurements serve, in particular, to integrate diverse in-situ observations over broad temporal and spatial scales.

Because of their variations in nature, location, and behavior, the committee has defined separate objectives for water, snow, floating ice, and glacial ice.

The highest-priority objective for the world's freshwater, sea ice cover, and glacial ice, and the single objective for the world's snow cover are of equal priority. The primary objectives for the study of the world's freshwater from space are as follows, in order of priority:

1. *To measure the spatial distribution and amounts of runoff, soil moisture, precipitation, and evapotranspiration over the Earth.*
2. *To measure the various land surface characteristics that control hydrologic responses and are affected by hydrologic change.*
3. *To measure past states in hydroclimate as a guide to possible future changes in the hydrologic cycle.*

The primary objective for the study of the world's snow cover from space is to measure its horizontal extent, depth, density, liquid water content, and albedo.

The primary objectives for the study of the world's sea and lake ice covers from space are as follows, in order of priority:

1. *To measure their horizontal extent, velocity, surface temperature, albedo, and topography, and to distinguish between different ice types.*
2. *To measure the wind velocity at their surfaces.*

The primary objectives for the study of the Earth's major glacial ice sheets and shelves are as follows, in order of priority:

1. *To measure the topography of their upper and lower surfaces, and their thicknesses, surface areas, surface temperatures, albedo, and internal structure.*
2. *To measure their surface velocities and strain rates and the iceberg discharge rates at their boundaries.*

These objectives are discussed in order below together with details of the measurement requirements for each. The committee emphasizes that these objectives address the study of the global hydrologic cycle for its own intrinsic importance. Because water, ice, and water vapor are also important in weather, climate, and global biogeochemistry, complementary objectives concerning the hydrologic cycle appear in Chapters 4, 7, and 8, devoted to weather, biogeochemistry, and climate, respectively.

Fresh Water

Objective 1

Measure the spatial distribution and amounts of runoff, soil moisture, precipitation, and evapotranspiration over the Earth.

Runoff is the discharge of water through surface streams. Although precipitation is the ultimate source of runoff, most of this input (71 percent in the United States) is lost as evapotranspiration. The balance, which enters streams and groundwater systems, follows complex paths over variable time scales. Knowledge of runoff needs to be developed on a uniform basis for the whole world. Despite high temporal and spatial variability of runoff phenomena in arid and savanna regions such as West Africa, these regions have the fewest stream gauges. Instead, most of the world's in-situ hydrologic monitoring occurs in regions of minimal hydrologic variability, such as western Europe and the eastern United States. Moreover, the knowledge of extreme runoff events, such as floods and low flows, is incomplete because these events are rare occurrences at any one observation point. Floods take place over the entire planet, however, and many spectacular examples can be studied each year (Figure 6.1). Flooding from tropical storm Agnes (1972) was the greatest natural disaster in monetary terms in the history of the United States ($3.5 billion in damages). Clearly, the importance of such events in water management requires an improved understanding of their occurrence, operation, and processes. By utilizing a global observation system, extreme hydrologic phenomena, such as floods, can be studied in their chance occurrences around the world.

The 16 largest rivers account for about half the total world runoff of water from the land to the oceans. Most of these rivers are in tropical or arctic regions and therefore have received little study. The Amazon River alone carries nearly 20 percent of all the water discharged to the sea by rivers on the Earth. Because of the importance of big rivers in global transfers of sediments, nutrients, and biochemical elements, special attention should be given to studies of dynamical processes in all the world's largest rivers.

Soil moisture is water in the unsaturated aerated zone of the subsurface that is accessible to plant roots. Soil moisture is the critical factor in food production. Its direct measurement would allow crop yield prediction. Soil moisture is also an important interactive parameter with the general atmospheric circulation, as discussed in Chapter 4.

Determinations of the areal extent and intensity of precipitation are needed to predict plant growth, water supplies, and flood hazards. Precipitation has already been discussed "as a component" of mesoscale atmospheric dynamics. Its magnitude and variation must be known (1) on the scale of individual storms to predict flood hazards, and (2) over broad regions for monthly and seasonal models of biological productivity.

FIGURE 6.1 Landsat image of an area in southwestern Queensland, Australia, affected by monsoonal flooding in January 1974. This drainage course, Cooper Creek, is dry except for extreme floods. The scene is 185 km across.

Evapotranspiration is the proportion of precipitation returned to the atmosphere by direct evaporation, by the transpiration of vegetation, or by sublimation from snow and ice. The atmospheric water vapor transport capacity is called the potential evapotranspiration. The potential evapotranspiration in the United States varies from 50 cm/yr in cool-wet regions to over 200 cm/yr in the desert Southwest. Water deficiencies occur where potential evapotranspiration exceeds precipitation, as it does over much of the world. Actual evapotranspiration must be known for agricultural practices, water supply, and weather/climatic determination. However, hydrologists generally determine this term as a residual in water balance calculations. An important advancement would be achieved if evapotranspiration could

TABLE 6.1 Summary of Data Requirements for Global Freshwater Studies

Hydrologic Element	Resolution for Basins of Various Sizes (m) Small (100 km²)	Intermediate (100–1000 km²)	Large (1000 km²)	Accuracy	Frequency
Surface water					
Areal extent	10	30	100	±5%	1–4 days
Floods	10	30	100	±5%	1–24 h
Floodplains	10	30	100	±5%	5 yr
Groundwater evaluation	30	30	30		Aperiodic
Drainage basins					
Areas	30	30	100	±1%	10 yr
Channels	30	30	100	±5%	5 yr
Cover	100	100	100	±1%	Seasonal
Slope	30	30	100	±1%	5 yr
Evapotranspiration	100	1000	5000	±1 mm	Daily
Soil moisture	100	300	1000	±10%	1–3 days
Precipitation	100	1000	5000	±5%	6 h

be estimated by orbital measurements combined with an appropriate predictive model.

MEASUREMENT REQUIREMENTS. Resolutions, accuracies, and frequencies of measurement (summarized in Table 6.1) are dictated by the requirements of numerical models and diagnostic studies of water supply, hydrologic hazards, and hydrologic influences on weather and climate. The spatial and temporal scales of these concerns may be widely disparate, so data requirements for a given hydrologic element vary with the required data use. Global average residence times vary from but a few days in plants, rivers, and the atmosphere, to several months in soils and snowpacks, to several centuries in groundwater and glaciers. Moreover, the dynamics of transfers can range from minutes in thunderstorms and flash floods, to years in lake and glacier margin changes.

Space-based measurement requirements for surface water, groundwater, evapotranspiration, soil moisture, and precipitation will be discussed separately. The committee emphasizes that *in addition to the need for measurements from satellites to address the hydrology of land surface areas, there is a pressing need for in-situ studies, particularly in the verification of satellite-based measurements of soil moisture, precipitation, and vegetation*. Although these in-situ studies are also emphasized in other sections of this report (troposphere, biogeochemical cycles, and climate), they are mentioned here to emphasize their added significance for hydrology. Moreover, the stricter observational requirements for hydrologic applications (Table 6.1) may dictate more intensive ground-truth studies than indicated by other purposes. For example, small basin studies (less than 100 km^2) will require the intensive hydrologic monitoring of selected study basins for local precipitation, soil moisture, streamflow, sediment yield, and other factors. Such study basins, which would be simultaneously monitored from space, should be located in a variety of hydrologic settings. Existing experimental catchments could be utilized in such verification studies.

SURFACE WATER. Measurements of surface water involve the location, areal extent, volume estimation, and continuous monitoring of temporal variations in reservoirs, lakes, ponds, and other surface water bodies. There are also needs for the following: (1) analysis of the spatial and temporal variation of shoreline and stream channel positions; (2) mapping the extent and damage of floods in progress; (3) delineation of boundaries for flood hazard zones; and (4) mapping and delineation of wetlands, marshes, and estuaries. These requirements can generally be met by high-resolution imaging visible/infrared sensing systems. Resolution to 10 m would be required in small drainage areas.

It would be useful to develop orbital techniques for the monitoring of runoff for studying the dynamics of sediment transport, thermal current patterns, nutrient cycling, and biotic productivity in surface water environments and the remote detection of pollutants in water.

Real-time measurements of floods in progress, studies of tropical rivers, and other situations involving probable cloud cover will require the use of radar imaging systems. Resolution requirements will be the same as for visible/infrared imagery systems.

GROUNDWATER. Groundwater studies from space consist mainly of identifying geologic and geomorphic indicators of appropriate conditions for groundwater development. Geologic structures (such as lineaments and fractures) and rock types suitable as exploration targets can be identified by procedures discussed in Part I of this report. It is also possible to interpret drainage patterns, landforms, and vegetation patterns associated with groundwater occurrence. These data are utilized to develop conceptual geologic models that predict groundwater recharge and identify areas for groundwater exploration. Visible, infrared, and radar imaging systems are most useful for this purpose. Resolution should be as high as possible, generally 30 m or better.

Underwater and submarine springs can sometimes be recognized by their thermal effects or by water turbidity plumes and influences on biota. Multispectral visible and infrared sensors are required with resolution of 30 m or better.

EVAPOTRANSPIRATION. There is a need to develop an accurate orbital remote sensing technique to repetitively estimate the spatial and temporal variability of evapotranspiration. This technique might utilize atmospheric models, relative biomass, relative surface albedo, and temperature measurements. Orbital remote sensing could be by visible and infrared imaging radiometers with resolution to 1 km. A scanning microwave radiometer (21-cm wavelength) could also be useful (10-km resolution).

SOIL MOISTURE. Sensing approaches are needed to monitor the spatial and temporal variability of surface and root zone soil moisture. This should be accomplished with a multispectral approach utilizing near infrared, thermal infrared, and active and passive microwave. Possible instruments would be a 21-cm scanning microwave radiometer (10-km resolution); 6-cm radar; and a visible-to-infrared radiometer. High-resolution soil moisture data (to 100 m) are required for small catchment studies.

PRECIPITATION. There is a need to develop the capability of making real-time estimates of precipitation, including maps of isohytes, rainfall intensities, and storm characteristics. Analysis will include studies of cloud area and albedo, cloud temperature, and passive microwave brightness of the ground. Some of these needs can be met by short-wavelength microwave radiometers over the oceans, a meteorological radar, and visible and thermal infrared radiometers. Resolution is needed to 1 km, except in small catchment studies, where 100 m resolution would be desirable. Techniques to address this objective are not yet in hand and will require development.

Objective 2

Measure the various land surface characteristics that control hydrologic responses and are affected by hydrologic change.

In addition to soil moisture, there are numerous conditions of topography, vegetative cover, land use, and rock and soil types that influence the amounts and rates of mass and energy transfer through the hydrologic cycle. These factors include the properties of channel networks, such as their areas, drainage densities, gradients, and connectedness. Many of these factors are experiencing progressive anthropogenic change through urbanization, deforestation, desertification, and irrigated agriculture. The exposure of bare ground by changes in vegetative type and/or cover will lead to immense changes in erosion and sedimentation. Arid, savanna, and semiarid regions are known to be much more sensitive to climate-induced change than humid temperate regions. Societal response to future climatic change presently occurs without critical information, since the existing data base relevant to assessment of future environmental change relies heavily on ground-based studies in humid-temperate regions. Global monitoring of environmental change can expand this data base into the data-sparse regions that are of most pressing concern. This objective is closely related to (and overlaps somewhat) the third primary objective for continental geology identified in Part I of this report, namely "to measure temporal changes in geologic conditions at the Earth's surface." This close relationship should be taken into account in the implementation of these two objectives.

The average annual soil loss from croplands in the 48 coterminous United States is 20 tonnes/hectare (2 kg/m^2). Total annual soil loss in the country exceeds 3 billion tonnes (3×10^{12} kg). This soil loss is concentrated at gullies and other easily monitored areas of accelerated erosion. Eroded sediment moves through the fluvial systems to sinks at reservoirs and eventually to the coastal zone. The mass transfer of essential topsoil is even more crucial in the tropics, where 6 million hectares (60,000 km^2) are converted to agriculture each year. In addition to lost productivity, this change increases the incidence of flooding, reduces baseflow, and decreases transpiration. It is thus both a cause of and a response to hydrologic change. Despite billions of dollars of site-specific research, the problem has continued to expand to its present global proportions. The threat to world food supply alone justifies a global initiative to deal with this concern.

MEASUREMENT REQUIREMENTS. A summary of measurement requirements appears in Table 6.1. Drainage basin characteristics are critical in the transformation of water input (precipitation) to output (runoff and sediment yield). Moreover, the channel network densities, gradients, and patterns are adjusted to factors of climate, rock and soil type, and land use. High-resolution mapping and quantitative characterization of drainage basin properties can therefore serve to evaluate a number of interrelated parameters. Visible and infrared imaging systems and imaging radar systems with high spatial resolution (10 to 30 m) are essential for this purpose. Stereo images are required for gradients and topographic data, which are necessary in calculating runoff discharges. It would be useful to have fully automated procedures to delineate networks, drainage areas, and patterns, and to make this stream network compatible with statistical hydrogeomorphic procedures that estimate hydrologic parameters from fluvial morphology. The type and density of vegetative land cover in drainage basins is needed to evaluate hydrologic effects of deforestation, desertification, and urbanization. Cover can be evaluated with visible to infrared radiometers at 1- to 4-km resolution for effects on general circulation. However, catchment studies will require high resolution (to 100 m).

Objective 3

Measure past states in hydroclimate as a guide to possible future changes in the hydrologic cycle.

It is an irony of our times that many of the ancient geologic "experiments" in altered hydrologic regimen induced by Quaternary climatic change are being redone as a result of large-scale surface mining, forest clearcutting, interbasin water diversions, and other man-made alterations of natural fluvial systems. From this perspective, large-scale paleohydrologic studies can serve as analogic models for the consequences of future hydroclimatic change. The National Research Council report *Climate, Climatic Change, and Water Supply* (National Academy of Sciences, 1977) considers paleoclimatic research to be a promising approach to obtain better estimates of climatic variability and drought probabilities.

Through a combination of in-situ and orbital measurements, it is possible to obtain data on past global hydroclimatic change. Indicators of such change include certain landforms, as follows: river terraces, fluvial paleochannels, paleolacustrine features, marine terraces and strandlines, moraines, and other evidence of terminal positions for mountain glaciers and ice sheets. None of these indicators of past environmental change has yet been studied on a global basis. The orbital measurements of these features would have to be combined with ground studies of stratigraphy, dating, and sedimentology.

Radar images of the extremely dry Selima sand sheet of the eastern Sahara recently obtained by the Shuttle Imaging Radar have revealed the phenomenal potential of orbital remote sensing for paleohydrologic research. The radar penetrated up to several meters of sand cover to reveal sand- and alluvium-filled valleys. The drainage systems were carved at times when this hyperarid region was subject to extensive erosion by running water, probably during pluvial episodes of the Quaternary.

Snow Cover

Objective 1

Measure the horizontal extent, depth, density, liquid water content, and albedo of the world's snow covers.

TABLE 6.2 Summary of Minimum Observation Requirements for the Cryosphere

Problem	Variable	Observation	Accuracy	Resolution	Time
Snow cover	Extent	Percent of area	10%	50 km	7 days
	Thickness	Area average	10%	50 km	2 weeks
	Density	Area average	10%	50 km	2 weeks
	Water equivalent	Area average	10%	50 km	2 weeks
	Grain size	Area average	10%	50 km	2 weeks
	Albedo	Area average	4%	100 km	2 weeks
Sea and lake ice	Boundaries	Line position	10 km	10 km	30 days
	Concentration	Area average	10%	50 km	30 days
	Ice type	Percent of area	10%	50 km	30 days
	Motion	Point displacement	1 km/d	10 km	7 days
	Thickness	Area distribution	1 m	25 km	30 days
	Leads	Percent of area and orientation	10%	50 km	7 days
	Surface roughness	Area distribution	1 m	20 km	30 days
	Ice surface temperature	Area average	2 K	20 km	7 days
	Snow characteristics	Area average	See Snow cover above		
	Sea surface temperature	Area average	2 K	20 km	7 days
	Wind velocity	Area average	2 m/s	50 km	3 days
	Ice islands	Point location, size	2 km, 100 m	2 km, 100 m	30 days
	Icebergs	Point location, size	2 km, 100 m	2 km, 100 m	30 days
Ice sheets and shelves	Surface elevation	Profile	2 m	50 km	n/a
	Elevation change	Change in profile	0.5 m	50 m	10 yr
	Boundaries	Line profile	0.5 km	0.5 km	10 yr
	Thickness	Line profile	10 m	50 km	10 yr
	Accumulation rate	Area average	20 cm/yr	50 km	10 yr
	Surface temperature	Area average	2 K	50 km	10 yr
	Surface velocity	Point displacement	1 m/yr	n/a	10 yr
	Internal properties	Profiles	varies	50 km	50 yr
	Condition at ice-rock interface	Profiles	varies	50 km	50 yr
	Iceberg discharge	Regional average	10%	n/a	5 yr

Accurate measurements of the horizontal extent and albedo of snow are required for determining the surface and planetary radiation budgets. Measurements of the extent, depth, density, and liquid water content of snow are necessary for determining total precipitation and spring melt volumes. A summary of the minimum required accuracies and minimum spatial and temporal resolutions for these measurements is provided in Table 6.2.

Recent work using passive microwave sensors has been encouraging in that snow depth and water equivalent appear to correlate with observed brightness temperature, which tends to decrease as snow depth increases. However, this relationship has not as yet been defined quantitatively, except for specific areas and times of the year. Present studies suggest that shorter wavelength microwaves are more sensitive to changes in snow depth than longer wavelengths, although this result may be due to the fact that only relatively shallow (less than 50 cm) snowpacks have been studied.

A multifaceted research program to explore the relationships between the properties of snow and its electromagnetic signature, blending theory, experiment, field observations, and technique development would clearly improve our ability to extract useful snow data from existing satellite and aircraft data. It would also provide a base of physical knowledge upon which to design new remote sensing systems for the observation of snow properties. Studies should be undertaken that include (1) controlled laboratory and field measurements, guided and reinforced by radiative transfer modeling, to determine how the dielectric and optical properties of different snow types vary with structure and wetness; (2) studies of physical processes occurring within the snowpack to determine how snow crystals metamorphose and how the pack evolves and stores and then releases water; (3) the development and standardization of field techniques for characterizing snowpack properties; and (4) the development of a variety of physical process models that utilize satellite snow data as input.

The analysis of existing visual and microwave imagery to extract snowpack information should also be continued. The limited available data set has already proven both interesting and useful, indicating that variations in the extent and duration of snow cover reflect short-term climatic fluctuations. Although it has been possible to measure snow extent using satellite imagery since 1966, a number of improvements can still be made. For instance, at typical optical wavelengths, snow and clouds have similar signatures, making their differentiation in images subjective. It is now known that at wavelengths of 1.5 to 1.6 μm the reflectivities of snow and clouds can be differentiated, but most spacecraft do not carry sensors responsive to radiation of this wavelength (the Thematic Mapper on Landsat-4 is an exception).

The committee also notes that good remote sensing techniques for determining the properties of a snow cover resting on an ice surface do not exist. Advances in this area would be very useful as the upper surfaces of lake ice, sea ice, ice sheets, and ice shelves are almost invariably covered with snow.

Sea and Lake Ice

Objective 1

Measure the horizontal extent, velocity, surface temperature, albedo, and topography of the world's sea and lake ice covers and distinguish between different ice types.

Precise measurements of the horizontal extent, surface temperature, and albedo of sea ice are required for determination of surface and planetary radiation budgets, for computation of heat transfers from ocean to atmosphere, and for diagnosing climatic change. Measurements of temperature, ice type (first-year or multiyear), and ice velocity are necessary for understanding the dynamics and thermodynamics of ice. The required measurement accuracies and spatial and temporal resolutions are summarized in Table 6.2.

To measure ice extent, one must be able to distinguish between ice and open water. This distinction can be obtained by both passive microwave (low resolution) and active microwave (high resolution) systems. In fact, passive microwave systems have been used for some time to map ice extent for both scientific and operational purposes. At present, map-format active microwave data are limited to the brief set of Synthetic Aperture Radar (SAR) observations made from Seasat. This imagery clearly shows the larger leads and the ice edge in great detail. It is difficult at some frequencies, however, to distinguish reliably between calm open water and flat first-year ice. Ice extent and concentration can also be observed with visible and infrared sensors, but these observations are limited by clouds (IR) and by clouds plus darkness (visible and IR), making it impossible to obtain observations at regular time intervals or during major storm passages.

The ice velocity field can be observed with a variety of sensors. The most promising system is the SAR, with its high resolution and its ability to function under all weather conditions. Recent studies have shown that it is possible to track numerous sequentially identifiable ice features on scales of less than 10 km. Figure 6.2 should give the reader a feel for the wealth of detail that can be observed in a Seasat SAR image. Weather permitting, similar observations can be obtained from visible and infrared sensors.

Recent studies using the Temperature Humidity Infrared Radiometer (THIR) onboard the Nimbus-7 satellite indicate that snow surface temperatures can be measured to within 2 K during cloud-free periods. Such measurements are of some urgency because they are an essential portion of any scheme that hopes to unravel the thermodynamics of polar pack ice.

FIGURE 6.2 A Seasat SAR image (Rev. 1382, October 1, 1978) of pack ice in the Beaufort Sea showing floes crossed by bright ridges and separated by dark leads. The very high return feature located just north of the center of the image is believed to be an ice island fragment in that known ice islands have been observed to give similar high returns. As ice islands are major hazards to offshore operations, it is very desirable to be able to track their movement.

Distinctions between first-year and multiyear ice are obtainable with infrared sensors as well as with both active and passive microwave systems. We do not yet know whether ice property distinctions within a general ice type are also possible, but it would appear probable. Such distinctions would clearly be useful as ice type changes commonly correlate with ice thickness and ice property changes. It would, of course, be desirable to be able to directly determine sea ice thickness from space. However, such developments do not appear likely as sea ice is an extremely high loss dielectric.

Ice roughness and surface topography are also useful in estimating ice volumes and studying ice dynamics. The backscatter as observed by the Seasat scatterometer is sensitive to changes in the roughness of the upper ice surface and shows distinct differences between ice and water. It is believed that eventually scatterometer observations can provide estimates of the total amount of ridged ice. Laser altimetry also shows promise for profiling the upper surface of sea ice. However, because of the larger footprint of the laser beam when measurements are made from space, these observations would appear to be more useful in studying the mass balance of the ice than in observing the distribution of pressure ridge sails.

It should be noted that thorough ground-truth studies are necessary to validate interpretations of satellite imagery of sea and lake ice. These studies require surface parties to make high-quality determinations of dielectric constants, backscatter coefficients, and net emissivities of different sea ice types and to identify currently perplexing features seen in satellite imagery.

Objective 2

Measure the wind velocity at the surfaces of the world's sea and lake ice covers.

Knowledge of the wind velocity is necessary to understand the dynamics of floating ice and to predict its motion. At the present time the surface wind vectors within areas of pack ice are calculated from surface pressure observations obtained by environmental data buoys. (Scatterometer techniques that are quite successful in determining wind velocities over the open ocean are not useful when ice occurs in the field of view.) Techniques for measuring atmospheric pressure at the Earth's surface (from which winds can be calculated) should be explored further, as techniques that work over sea ice should also be successful over land.

For understanding ice dynamics, vertical profiles of ocean velocity are also important. These observations are, at present, only obtainable from specially equipped data buoys. Measurements from space would not appear to be feasible since the ice is a barrier, limiting access to the ocean. At present, the ocean velocity profile is probably the least known parameter in sea ice forecast models. If high-quality estimates of air and water stress on ice could be made and combined with good ice movement observations, it would be possible to improve our estimates of internal ice stress (the stress that is transferred laterally through the ice). For the foreseeable future we will have to supplement remotely sensed satellite data with data collected by buoy arrays and relayed to land-based receiving stations by satellite.

Glacial Ice

Objective 1

Measure the topography of the upper and lower surfaces, thicknesses, surface areas, surface temperatures, albedo and emissivity, and internal structure of the Earth's major glacial ice sheets and ice shelves.

Measurements of the thickness and of the topography of the upper and lower surfaces of ice sheets are essential for modeling their dynamics and stability. Accurate determinations of surface temperature, albedo, and emissivity are required for computations of the planetary and surface radiation budgets and for estimating surface accumulation and ablation rates. The necessary accuracies and spatial and temporal resolutions for these various measurements are summarized in Table 6.2.

The surface elevations of the major ice sheets are poorly known. Radar altimetry already has made a significant contribution toward improving this situation for Greenland south of 72°N and east Antarctica north of 72°S. Recent studies have shown that if a laser altimeter with a range precision of ± 10 cm, a footprint diameter of 70 m, and a sampling rate of 20 Hz were deployed into polar orbit, the data would accurately profile all but the roughest ice sheet areas. Glaciologists would be able to delineate (through the surface elevation pattern) drainage basins, ice flowlines, ice streams, grounding lines between the ice sheets and floating ice shelves, and the seaward margins of the ice cover. As detailed surface profiles are proxy indicators of the basal conditions and ice creep properties, profile studies would also contribute to our understanding in these areas.

The required ice surface temperature measurements are possible with existing systems. Systematic measurements of the variations of the temperatures of the large ice sheets and ice shelves are, however, incomplete. The desired radiometric resolution is 1 K, although a 2 K resolution would still result in useful data. Such measurements would also be very useful in sea ice and snow studies, and would contribute to improved determinations of the emissivity of snow and ice surfaces, which could then be calculated directly from observed surface and brightness temperatures.

Recent studies of the microwave emissivity of dry snow facies in

Antarctica and Greenland have shown that the accumulation rate can be calculated by combining the mean annual emissivity (obtained from the mean annual brightness temperature divided by the mean annual surface temperature) with information on snow crystal size (which, in turn, is controlled by the accumulation rate and the mean annual surface temperature). Although this approach needs more study and verification, in principle it appears quite plausible. If it can be developed into an operational technique, it will provide valuable accumulation data that, at present, can only be obtained by field traverses, a time-consuming and costly procedure.

Sequential surface elevation profiles would allow measurements of changes in surface elevation over time as the ice sheet thickens and thins. For example, the best current guess for an average mass balance for Antarctica is positive by about 20 percent, implying that on the average surface elevation is increasing by 3 cm/yr. If we could measure surface elevation to within ± 10 cm using laser techniques, we should be able to verify the +20 percent estimate by replicate readings taken over a 3- to 5-year period. For measurement accuracies of less than ± 10 cm, longer periods would be required between readings.

Radio-echo sounding of the thickness and internal structure of large ice sheets is now commonplace. Not only can we obtain ice thicknesses and the topography of the ice-bedrock interface, we can also determine the internal structure of the ice by observing a number of strong echos within it. Up to now, instrument packages have been carried either on the ice surface or, most commonly, in an aircraft, but these measurements could also be made from an instrument package deployed on a satellite. The resolution would be less than that resulting from the use of aircraft. However, there are large inaccessible areas of Antarctica and Greenland that have not been profiled. The satellite alternative therefore appears attractive, and the committee recommends that a feasibility and cost-benefit analysis of the use of satellite instrumentation for this purpose be carried out.

At the present, ablation cannot be measured directly, but we can measure several other parameters that are useful in estimating it; for instance, detailed surface elevation measurements would show snow and ice losses due to ablation. For such measurements to be useful, however, replicate observations would have to be made monthly (or even better, weekly) during the summer. Wet snow shows much higher microwave brightness temperatures than dry snow, so this fact can be used to map the snowmelt line as a function of time on large ice sheets. This is particularly useful in Greenland, but of limited use in Antarctica, where surface melt is less common.

Objective 2

Measure the surface velocities and strain rates of the Earth's major glacial ice sheets and ice shelves and the iceberg discharge rates at their boundaries.

Accurate measurements of velocities, strain rates, and iceberg discharge rates are required for understanding the kinematics, dynamics, and mass balances of the ice sheets. Required accuracies and resolutions are given in Table 6.2.

Surface ice velocities (horizontal) show large variations from place to place within the same ice sheet. For instance, in the interiors of the sheets, surface motions of a few meters per year are typical. On the other hand, in major ice streams near ice sheet boundaries, velocities in excess of 1 km/yr have commonly been observed. No system for measuring such a range of surface velocities from space is currently in existence. It would be possible to utilize a system like Navsat for these observations, with the buoys being interrogated from space, but the electronics and power packages would have to be placed on the ice sheet surface. It would be far better if the target placed on the ice were totally passive. Another possibility would be to use radar reflectors in conjunction with a high-resolution satellite SAR system. Desirable resolutions would be 10 m or less. If individual targets can be tracked, then measurements of strains and strain rates become possible. Typical strain rates for large ice sheets are 10^{-5}/yr to 10^{-4}/yr, corresponding to a few meters per year increase in the length of a 100-km line.

These velocity and strain rate measurements are less demanding than the requirements necessary for the study of time-dependent deformation in seismic zones or the rates of motion between stable portions of the Earth's major tectonic plates (as discussed in Part I of this committee's strategy, an accuracy of at least 1 cm/yr at a high level of confidence is required for these latter studies related to solid earth dynamics). Developments in such systems should be monitored closely, keeping in mind the possibility of tailoring them for similar measurements on large ice sheets.

Although flow laws are commonly obtained from laboratory tests, satellite ice velocity and strain-rate observations would serve as field checks on experimental results. Information on whether the ice at the bed of an ice sheet is at or below the pressure melting point can occasionally be gained from observations obtained by radio-echo sounding, as there appear to be lakes at the ice-water interface at some locations under east Antarctica—a sure indication that the basal ice is at its pressure melting point. Although it would appear difficult to use satellite techniques to determine the degree of preferred crystal orientation in the lower portion of large ice sheets, once such a determination is made, it may prove possible to use radio-echo sounding to map the upper boundary of the oriented ice.

Iceberg discharge, iceberg drift in the open ocean, and changes in the boundaries of the major antarctic ice shelves (which, incidentally, occupy one-third of the antarctic coastline) could all be monitored by a SAR satellite system coupled with receiving stations placed on the antarctic continent. Such a SAR system might also provide some information on ice stream flow velocities by tracking the movement of crevasses.

ADVANCES IN THEORY AND MODELING

Attainment of the committee's goals for the global hydrologic cycle will require, in addition to the stated measurements, some specific advances in theoretical understanding and modeling capability. These advances are required in the areas of continental hydrology and sea and glacier ice research.

Hydrologic modeling has made important recent advances in the areas of understanding land surface moisture fluxes, in using ecological factors for the parameterization of soil processes, and in relating storm runoff to geomorphology. Observations from space are required for the verification and use of these new approaches. For example, vegetation, which can be economically surveyed only from space, serves a unique and useful role as an integrator of the spatially variable fields of soil properties and soil moisture. Proper parameterization of vegetation allows the derivation of transfer functions that delineate the relevant hydrologic factors. Similarly, the measurement of quantitative geomorphic factors, such as drainage density, basin shape, and channel gradients, can be applied to models of flood runoff and flood hazard evaluation.

Hydrologic models for land areas generally make use of point data sources (rain and stream gauges, evaporation pans, snow depth surveys, and so on) to predict one or several of the complex and interrelated elements of the hydrologic cycle. Models are commonly applied to a single drainage basin in order to predict streamflow or soil moistures over hourly to seasonal time scales. Such models do not admit feedback to the regional climate from either the state or the output of the catchment. Climatic factors (precipitation and temperature) serve as external inputs to such catchment models.

In contrast, tropospheric general circulation models that do treat surface hydrologic processes are necessarily simplistic, generally expressing the relevant hydrologic fluxes as linear functions of the average moisture content in a single soil layer. Their improvement requires better modeling of the critical physical processes at dynamically adequate (but computationally economical) time and space intervals. These new models must couple systems that operate on widely disparate temporal and spatial scales. Most important, the models need to be verified with global data sets. While such data sets exist for the current land surface state (i.e., soils, vegetation, land use, water surface, and snow cover), they are of widely disparate utility.

Global remote sensing can provide distributed hydrologic data of uniform quality for the verification of linked hydrologic-climatic models. The potential availability of such global data sets poses an important challenge to hydrologic modeling. Physically based models that promote system understanding and provide useful water resource predictions must be developed to keep pace with the wealth of the new global data sets. *The committee recommends development and improvement of hydrologic models as a basis for understanding that will lead to hydrologic prediction.* Hydrologic modeling must move beyond empirical correlation hierarchies and Monte Carlo simulation procedures to provide a true scientific approach for studying the hydrosphere (see *Scientific Basis of Water-Resource Management*, National Academy Press, 1982).

Satellite remote sensing data will be extremely useful in both producing and validating numerical simulations of sea ice behavior. Information derived from satellite remote sensing could be used in a variety of ways as input into numerical models. However, models that effectively utilize satellite information have not as yet been developed. The data would serve both to specify changing atmospheric and oceanic boundary conditions (air and water velocities and temperatures) and to periodically update the actual state of the ice. *The committee recommends development and verification of such models for the dynamics, thermodynamics, and maintenance of the world's sea and lake ice covers.*

When models like these become a reality, they will demand that a variety of remote sensing data be rapidly processed so that they can be utilized as model inputs in near-real time. This is a particular problem in SAR imagery, where it is desirable to track the motions of a large number of identifiable ice features in sequential imagery. This is now done manually and is very time-consuming. Such processes should be automated using modifications of existing pattern-recognition techniques. A related problem is the development of a capability for using pattern-recognition techniques to identify and measure a wide variety of additional ice parameters, such as the areal percentage of deformed ice, open water, multiyear ice, lead orientations and spacings, floe size distributions and shapes, and the presence of particular ice hazards such as ice islands or icebergs.

There is also a need to develop improved theoretical models of the electromagnetic and optical characteristics of sea and brackish-water ice. Current models are only poorly related to what is known about the structure of both materials. For instance, albedo may change by a factor of 2 to 3, depending on snow and ice age, grain size, and surface puddling, and it also varies significantly with wavelength.

As an example of the culmination of the studies suggested in the previous paragraphs, a combined satellite-borne remote sensing and sea ice modeling experiment should be carried out in the Bering, Chukchi, and Beaufort seas. These are not only regions of great interest to the United States, but they possess ice types and behaviors that are generally representative of most other sea ice regions.

The ability to accurately model and thus predict the behavior of the world's major ice sheets is essential for studies of climatic change on 100-year and longer time frames and essential for the study of mechanisms responsible for the great Pleistocene ice ages. *The committee recommends development and verification of models for the dynamics and maintenance of the world's major glacial ice sheets and ice shelves.* We must continue to expand and refine present numerical models of the dynamics and thermodynamics of large ice sheets and consider ways to efficiently input satellite remote sensing data into such models. This data assimilation problem is somewhat similar to that encountered in sea ice modeling, although the models themselves are quite different.

The committee also notes that arrangements should be made to access cryological data from satellite programs run by the Department of Defense. For instance, multifrequency passive microwave data obtained by the Defense Meteorological Satellite Program would prove valuable in studying changes in the extent and makeup of polar ice pack. Arrangements should also be made to receive data from several foreign satellites scheduled for launch in the near future: the European Space Agency's proposed 1988 launch of a combined SAR and scatterometer system, the projected Japanese launch (1988) of a SAR system believed to be similar to the Seasat system, and the projected Canadian launch of a C-band SAR system (1990). All of these systems will generate valuable imagery of arctic seas and glaciated areas of interest to U.S. investigators. *To receive such SAR data the committee recommends that a receiving station be established in Alaska, as the data flow rate is so high that data can be obtained only when the satellite is within line-of-sight*. Such a program would significantly contribute to our understanding of the ice circulation in the Arctic Ocean, and could contribute to the eventual establishment of such receiving stations in Antarctica.

In addition, sets of observations made from a Shuttle mission in polar or near-polar orbit could effectively answer many image interpretation problems in cryology and questions relating to designing optimum observing systems that could later be deployed via free-fliers. For instance, in one mission using a suitable SAR system, sea ice imagery could be obtained at different frequencies, look angles, polarizations, and resolutions. Associated field observations would then allow investigators to further develop correlations between image features and real ice features. Some aspects of the geophysics of large ice sheets could also be studied quite effectively from Shuttle missions. Such a data set could be taken as characterizing the state of the ice sheet at an instant in time. Later these data could be compared with similar data taken at an appropriate time in the future.

7
Goals and Objectives for Global Biogeochemical Cycles

INTRODUCTION

With water and oxygen, four elements—carbon, nitrogen, phosphorus, and sulfur—are of special interest in the study of this planet. Because of life, each of these four follows a closed loop through increasing and then decreasing molecular energy states. The dynamics are the consequence of physical, chemical, biological, and geological processes that operate across a wide spectrum of time scales. In the absence of a significant disturbance, these processes define a natural cycle for each element with approximate source-sink balances that result in a quasi-steady state for the cycle, at least on time scales less than a millennium.

However, human activity since the beginning of the Industrial Revolution has increased to such an extent that it must now be regarded as a significant disturbance to the biogeochemical cycles of the planet. The magnitude of this activity is extensive, and the effects are approaching an important stage: certain indicators of the state of particular cycles, such as the levels of atmospheric CO_2 and CH_4 for the carbon cycle, have moved well outside their recent historical distributions (Figure 7.1). Similarly, perturbations to the nitrogen cycle are revealed in currently measured increases in the concentration of atmospheric N_2O. Increased mobilization of sulfur through fossil fuel combustion has led to increased concentrations of sulfate in precipi-

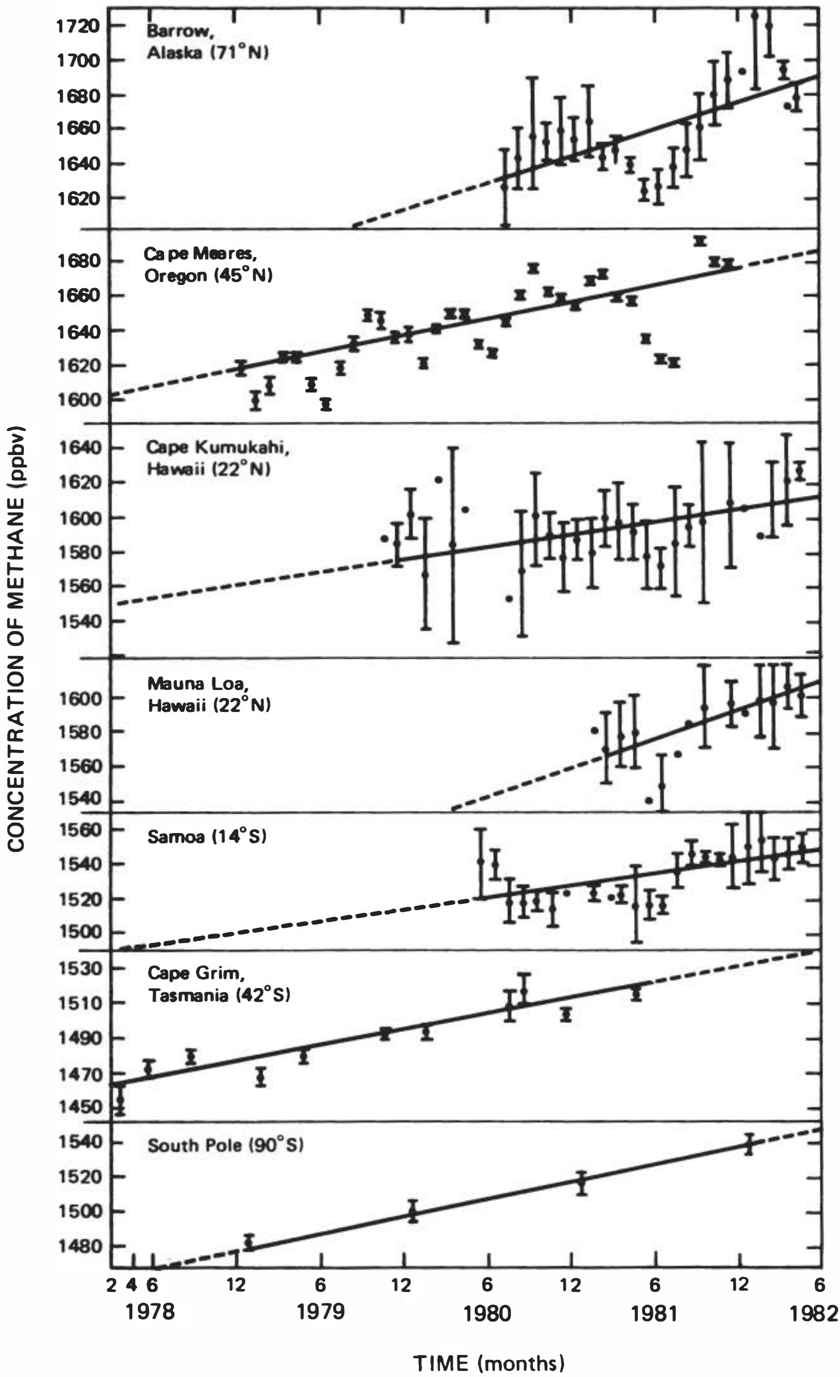


FIGURE 7.1(a) Trends in CH_4 at seven globally distributed locations.

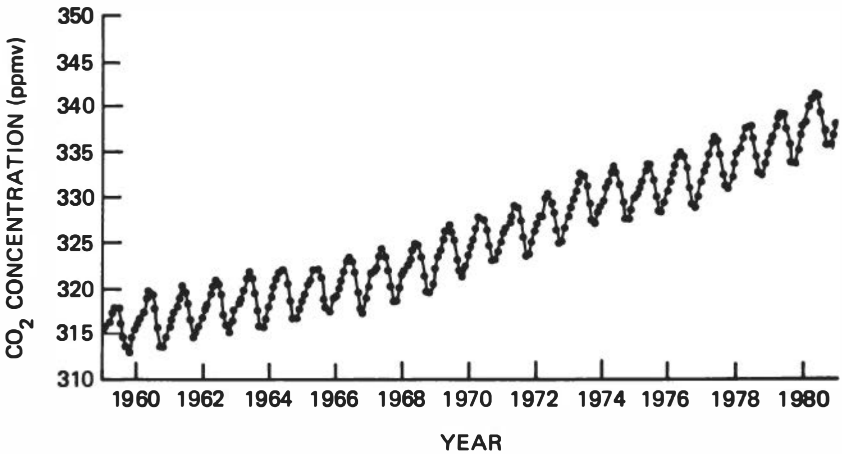


FIGURE 7.1(b) Trend in CO_2 concentration at Mauna Loa, Hawaii.

tation, and it is difficult to identify a major river or estuary that has not been affected by the addition of phosphate from agricultural, urban, or industrial sources.

The human race has been eminently successful in using its mastery of science and technology to increase the production of food for the needs of expanding populations. It has done so by altering natural and traditional patterns of land and water use, by utilizing large quantities of fossil fuel energy, and by congregating people and waste with increasing densities. Serious questions have now been raised, and new knowledge is needed to address them:

1. What are the present states of the major biogeochemical cycles?
2. What were their states prior to anthropogenic perturbations?
3. What may be the future state and the likely results of these future states?
4. What must be known to permit us to reverse or stabilize anthropogenically induced trends if and when this becomes desirable?

The importance of these questions is readily illustrated by reference to the carbon cycle. Although knowledge of the carbon cycle is a key to comprehending the biosphere, the cycle is not well understood. Uncertainty centers partly on the role of terrestrial biomes, in which at least two factors govern the level of carbon storage. The first and most obvious factor is the alteration of the Earth's surface, such as the conversion of natural forests and grass lands to agriculture, which often results in a net release of CO_2 to the atmosphere. The second and more subtle factor is the possible change in net ecosystem production, and hence carbon storage, that results from changes in other global cycles. For example, the burning of fossil fuels not only releases large amounts of carbon to the atmosphere, but also increases the inputs of nitrogen and sulfur. Some fraction of these compounds must enter forest biomes through precipitation and dry deposition. Will this fertilization of forests stimulate both the fixation and the storage of carbon, or will the acidity associated with the nitrogen and sulfur deposition actually inhibit forest growth?

As another example, the harvesting of forests and the creation and managing of agricultural land often result in the loss of nitrogen to the atmosphere and adjacent aquatic ecosystem. Do such losses reduce the carbon storage capacity for the system? What are the magnitudes of nutrient inputs to aquatic systems when adjacent terrestrial biomes are disturbed? What are the consequences of these inputs? Will river eutrophication increase carbon storage? Will it increase N_2O fluxes to the atmosphere?

Clarification of the first factor by the measurement of extent and change in area of the relevant biomes is obtained readily from analysis of satellite imagery. Clarification of the second factor, however, necessitates measuring the amount of biomass per unit area in a given system, the annual dynamics of this biomass, the change in this biomass following the disturbance, and the flux of trace gases, carbon, and essential nutrients in both the disturbed and the undisturbed states of the biomes. This will require advances in remote sensing for the global picture and extensive in-situ studies of the biome dynamics.

This chapter addresses the major global pools (namely the terrestrial biomes, the oceans, and the troposphere) of carbon, nitrogen, sulfur, and phosphorus, and the fluxes between them: the global biogeochemical cycles. Of particular interest is how these cycles may have been disturbed by man, and hence how these interlocking systems interact in transition phase. Since even the most rapid processes of adjustment among the reservoirs take decades, new equilibria are far from being established. In a sense, therefore, these human-induced perturbations and the system's subsequent responses constitute an ongoing biogeochemical experiment at the global level. Consequently, if the right questions are asked and the appropriate data of sufficient accuracy are collected in a timely fashion, then this experiment holds the promise of providing major new insights into the basic processes that support life on this planet. There is no doubt that observations from space provide the only practical method for obtaining much of the needed data over the next 10 to 15 years.

The state of knowledge and major problem areas for each of the four major biogeochemical cycles are discussed below as a preface to the committee's proposed strategy for the study of the biogeochemical cycles from space.

The Carbon Cycle

There are two central chemical processes in the carbon cycle: aerobic oxidation and anaerobic oxidation. Increases in the rate of aerobic oxidation are the probable cause of the observed increases in atmospheric CO_2; increases in the rate of anaerobic oxidation may be the cause of the observed buildup of CH_4. The case of CO_2 exemplifies many of the limitations in our current understanding of global cycles as well as important gaps in current data sets; therefore it will be addressed in some detail here.

The possible effects of human interference with the natural cycle of carbon by burning fossil fuels, harvesting forests, and converting land to agriculture are reflected most clearly by the phenomenon of increasing concentration of atmospheric CO_2 (see Figure 7.1(b)). If current trends continue, the atmospheric concentration will exceed 600 parts per million by volume (ppmv) by the year 2040—more than 2 times the preindustrial level. The increase in CO_2 is important because, in contrast to atmospheric O_2 and N_2, CO_2 absorbs infrared radiation emitted by the Earth and prevents the escape of some of the normally outgoing radiation. This is known as the "greenhouse" effect and is addressed further in Chapter 8.

At present, our ability to interpret the carbon cycle (Figure 7.2) and thus predict future CO_2 concentrations is confounded by unresolved imbalances in the carbon budget. Simply stated, the annual budget equation (Table 7.1) does not balance unless (1) fertilization effects, either terrestrial or aquatic, partly offset deforestation minus regrowth, (2) the imbalance diminishes from reductions in the estimate of the rate of deforestation or increases in the regrowth, (3) the oceanic uptake is underestimated, or (4) there are natural variations in the global rate of carbon uptake by the biota that are not yet recognized. The question of which combination of these possibilities is most likely needs to be addressed.

The present concentration of CO_2 in the atmosphere is about 340 ppmv, which is equivalent to about 730×10^{15} grams of carbon (g C). During one year, seasonal differences in photosynthesis and respiration within the biosphere create an oscillation in the atmospheric CO_2

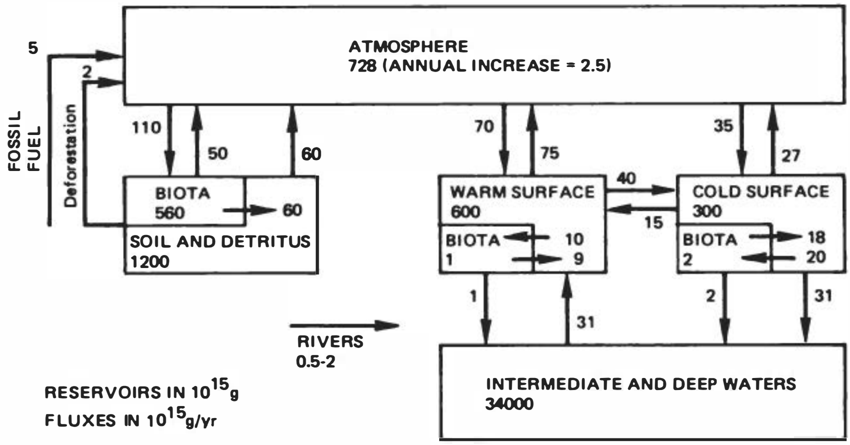


FIGURE 7.2 Global carbon cycle (unbalanced).

concentration, with an amplitude of roughly 5 ppmv, or 11×10^{15} g C/yr. A few attempts have been made to detect changes in the amplitude of this oscillation as a way to infer changes in the size of biospheric pools of carbon, but the results have been inconclusive.

Estimates of the amount of carbon in living organic matter on land vary between 450 x 10^{15} and 900 x 10^{15} g C, and although soil organic matter (humus) is a major active reservoir in the global carbon cycle, there is insufficient information on its size and activity. Estimates range from 700 x 10^{15} to 1800 x 10^{15} g C. Estimates of total primary production (carbon fixation), respiration, and detrital decay rates also vary greatly. There are two principal reasons for this uncertainty: (1) the method of scaling from selected local sites of measurement to biome-wide estimates is not rigorous, nor for many systems is the available in-situ information sufficient, and (2) uncertainties exist about the geographic extent of different biomes and soil types.

The magnitude of the net release of carbon from vegetation and soils of the world as a result of land use changes remains largely unknown. The problem of calculating this release centers on two general but important factors: the rate of land use change and the response of biota to disturbances. It is surprising and frustrating that, even today, estimates of the current rate of conversion of closed canopy tropical forests to agricultural land vary from 3.5 x 10^4 km^2/yr to 10 x 10^4 km^2/yr. Analysis of the biotic response to such disturbances has been even more difficult; improved description of biotic responses requires better measurements of net ecosystem production and/or ecosystem carbon stocks following such disturbances.

TABLE 7.1 Annual Carbon Budget

Input of Carbon as CO_2 into Atmosphere	
Fossil fuel	5×10^{15} g C/yr
Deforestation minus regrowth	2×10^{15} g C/yr
	7×10^{15} g C/yr
Uptake of CO_2	
Atmospheric increase	2.5×10^{15} g C/yr
Oceanic uptake	2.5×10^{15} g C/yr
Fertilization effects	?
	5×10^{15} g C/yr + ?

Calculations of the net carbon loss from the global biotic inventory, which attempt to take into account the uncertainties concerning disturbance rates and biotic response, indicate that from 1860 to 1980 the total loss was 150×10^{15} g C, with a current annual loss rate between 1×10^{15} and 3×10^{15} g C/yr. However, without far more accurate information about disturbance rates and ecosystem responses, it will be impossible to appraise with confidence the validity of these numbers and thus the role of the terrestrial biosphere in the global carbon cycle.

The oceans are by far the largest active reservoir of carbon. Recent estimates of the total amount of dissolved inorganic carbon establish its range as 34,000 to $38,000 \times 10^{15}$ g C. Only a small fraction is CO_2 (mole fraction 0.5 percent); the bicarbonate ion HCO_3^- with a mole fraction of 90 percent and the carbonate ion CO_3^{2-} with a mole fraction of slightly less than 10 percent are the major forms of dissolved inorganic carbon. Although the oceans are the largest active reservoir of carbon and cover 70 percent of the globe, the total marine biomass is only about 3×10^{15} g C or just over 0.5 percent of the carbon stored in terrestrial vegetation. On the other hand, total primary production in the oceans is 30 to 40×10^{15} g C/yr, corresponding to 25 to 40 percent of the total primary production of terrestrial vegetation. However, only a small portion of this production results in a sink for atmospheric carbon, primarily through the sinking of particulate organic carbon, which decomposes in deeper layers or is incorporated into sediments. This downward flux has been estimated to be only 10 percent of the surface primary production rate; therefore it is currently in question as to whether primary production rates might have been sufficiently increased in response to human-induced changes of other cycles to produce a significant change in the flux of this particulate carbon.

Linked to the biologically mediated controls on CO_2 are the movement and mixing of oceanic water masses. In particular, turbulent mixing and the penetrative convection of surface water during deep water formation in polar regions creates a sink for CO_2 in high latitudes, and the balancing upwelling in low latitudes creates a source for CO_2. Estimates of the magnitude of the pole to equator difference in surface layer partial pressure range as high as 20 ppmv. Comparison of individual cold biologically active water masses and warm biologically inactive water masses reveals differences as great as 100 ppmv.

The net flux of atmospheric CO_2 into the oceans remains uncertain, although most current models suggest that between 40 and 50 percent of fossil fuel CO_2 is taken up by the oceans. If these models are correct, then there is an imbalance unless the biospheric source for CO_2 as estimated directly from land clearing patterns is in error.

Emissions of the biogenic and/or anthropogenic compounds CO, CH_4 and higher hydrocarbons, isoprene, and terpenes represent only a small fraction of the total carbon flux into the atmosphere. Nevertheless, these reduced carbon compounds play important roles in the chemical system that controls the levels of oxidizing species (OH, HO_2, and O_3) in the atmosphere. These compounds are also radiatively active and thus influence climate. At the present time, however, we do not know what is causing the 2 percent per year increase in atmospheric CH_4 observed over the past 5 years (see Figure 7.1). It could be due to either an increase in global biogenic CH_4 emissions or a decrease in global tropospheric OH levels (OH is the principal scavenger for CH_4) or a combination of both. Since OH is the single most important species involved in scavenging of both biogenic and anthropogenic species from the troposphere, a change in its concentration would have very significant consequences for future tropospheric composition and climate.

In summary, present uncertainties in our understanding of the carbon cycle lead to serious difficulties in balancing the current budget of atmospheric CO_2. There are a number of problems that must therefore be addressed: the extents and carbon contents of major terrestrial biomes, the factors controlling the internal routes for uptake and release of carbon, the processes that control the exchange of carbon (both oxidized and reduced) between the atmosphere, biota, and oceans, and finally the response of the carbon cycle to human perturbations.

The Nitrogen Cycle

There are three characteristic time scales in the nitrogen cycle: a long time scale (2 x 10^6 years) involving the flux of N_2 to and from the atmosphere; a much shorter time scale (1 to 30 years) involving the fluxes of nitrogen within the biosphere; and a time scale between these extremes involving the flux of nitrogen throughout the system associated with human activity.

The nitrogen cycle is complex. Nitrogen found in compounds as single atoms (so-called fixed nitrogen) is chemically versatile, occurring in a wide variety of valence states (-3 to $+6$). This versatility stands in contrast to the relative inertness of N_2, which is chemically stable due to the strength of the $N = N$ bond. Processes that break the $N = N$ bond (nitrogen fixation) are relatively slow, amounting to about 0.25 x 10^{15} grams of nitrogen per year (g N/yr), which gives atmospheric N_2 a residence time of about 2 x 10^7 years. The associated residence times (days to decades) for the various states and reservoirs of fixed nitrogen are, however, far less than for N_2. It may be noted that the land and ocean reservoirs of nitrogen in fixed nitrogen are only about 10^{-5} and 10^{-4}, respectively, of the nitrogen in atmospheric N_2.

The flux from molecular nitrogen to fixed nitrogen obviously must be balanced on time scales much less than 2 x 10^7 years by a return flux of similar magnitude. The recombination reaction (denitrification) is carried out biologically by bacteria in anoxic, organic-rich locations such as flooded soils and sediments and anoxic waters of the major coastal upwelling systems using NO_3^- and NO_2^- as the oxidizing agents.

In the absence of biological fixing and denitrifying processes, the atmospheric nitrogen cycle would be open, with lightning fixation leading potentially to accumulation of NO_2^- and NO_3^- in the oceans. Even with the requisite biology present, it is not clear how the global system acts to establish a balance between biological and lightning fixation and biological denitrification. No direct mechanisms have been identified that couple nitrogen fixation to denitrification, and indirect mechanisms are also not obvious.

Total nitrogen fluxes in the nitrogen cycle are about 10 times as large as the flux for fixation of N_2 alone. In particular, mineral nitrogen (NH_4^+, NO_2^-, and NO_3^-) is assimilated into terrestrial biomass at a rate of about 2.5 x 10^{15} g N/yr, and this influx to the biota is accompanied by an almost equal outflux resulting from decay of organic material (mineralization). There is roughly 70 x 10^{15} g N in the active soil pool as organic nitrogen, NH_4^+, and NO_3^-. The mean transit time for nitrogen in this major reservoir is therefore about 30 years, though there would be large variability in this transit time when viewed across different biomes. Tropical soils contain relatively little organic matter, and the transit time is considerably less. The opposite is true in boreal regions. In either case, the dominant form of stored nitrogen is organic nitrogen since the mineral forms of nitrogen are rapidly taken up by the vegetation, and when highly soluble (e.g., NO_3^-), there is the additional loss from being washed rapidly from the system.

Within the oceans, on the other hand, the pool of dissolved mineral nitrogen is larger than that of dissolved organic nitrogen except within the uppermost sunlit layers (the photic zone), where mineral nitrogen is an essential nutrient for phytoplankton and is consumed rapidly. Consequently, mineral nitrogen in the photic zone must be renewed either by internal recycling or by replacement from deeper layers where it is produced by bacterial decomposition of particulate and dissolved organic matter. Neither of these renewal processes is well understood.

The amount of fixed nitrogen in the atmosphere is very small since residence times for atmospheric NO_2 and NH_3 are only of the order of a few days. There are therefore marked spatial variations of these compounds in the atmosphere, and the global average picture is not generally representative of any single region.

Natural emissions of nitrogen from the surface to the atmosphere result from formation of volatile compounds, namely, NH_3, NO_2, NO, N_2O, and N_2, during the process of bacterial decomposition in the soil. In the atmosphere, the first three compounds are incorporated into aerosol particles and raindrops as NH_4^+ and NO_3^- ions and are returned to the soil and the sea by precipitation and particle deposition. N_2O, on the other hand, is comparatively inert. It ultimately decomposes into N_2 and NO in the stratosphere, and, as already mentioned in Chapter 5, NO plays an important role in photochemical reactions associated with stratospheric ozone. However, it is not known if there also exist important sinks for N_2O in the troposphere, a problem that adds additional uncertainty in understanding the nitrogen cycle.

Humans are demonstrably modifying the nitrogen cycle. First, the cultivation of legumes and the production of artificial fertilizers places over one-half of the global N_2 fixation process under the control of man. Second, improved tilling has increased the rate of decomposition of organic matter in the soil and thus the return of N_2 to the atmosphere.

Third, high-temperature combustion represents 10 to 20 percent of the total flux of fixed nitrogen to the atmosphere and is highly concentrated in the inhabited regions of the northern hemisphere. The combustion-produced nitrogen oxides have an important impact on atmospheric chemistry, biological productivity, and the acidity of precipitation in the northern mid-latitudes.

While the amount of nitrogen fixation controlled by man annually is significant compared to natural fixation, it is still small compared with the existing fixed nitrogen pools in the soil and in the oceans. These pools therefore will be influenced only slowly. It will take at least several decades before significant global changes may be expected due to man's activities; changes in particular localities such as soil and water systems may appear much sooner. But for the very reasons that it would be several decades before any significant global changes could be apparent, it will also take an equally long time for conditions to return to an earlier balance once a change is detected.

There are a number of important issues concerning the nitrogen cycle. What is the magnitude of the nitrogen fixation rate in major biomes? How much of this fixation is determined by natural processes unaffected by man, and how much is under advertent or inadvertent control of humans? How is the fixation rate changing? Are human or natural influences in the nitrogen cycle causing a decline in the fertility and productivity of major terrestrial biomes? Are stores of nitrogen in major soil systems deteriorating? What effect does anthropogenic nitrogen have on rivers and coastal biomes? Is the nitrogen in sewage damaging or enhancing marine biotic resources? Have NO, NO_2, and N_2O emissions from combustion and agricultural soils enhanced global concentrations of these gases? If so, what effects may be expected on other important species, such as tropospheric ozone, which is produced by photodissociation of NO_2?

The Phosphorus Cycle

Phosphorus is an essential element for life. It is relatively abundant in the crust of the Earth, but it exists principally as insoluble minerals (apatite, iron phosphates) or as absorbed phosphate. These forms are not available for biological uptake, and consequently, phosphorus is often a limiting nutrient in soils, lakes, and perhaps even marine systems. Atmospheric transfer processes are unimportant for phosphorus, in contrast to carbon, nitrogen, and sulfur. Rather, the major phosphorus exchanges are associated with dissolved and particulate transport in rivers, and with weathering processes and diagensis in soils and sediments. There are thus important connections between the hydrologic cycle and the phosphorus cycle.

Modern man has made a major impact on the mobility of phosphorus. The prehistoric phosphorus flux from land to oceans was probably about 10 x 10^{12} grams of phosphorus per year (g P/yr), while as a result of industry and agriculture the present rates are much higher; about 25 x 10^{12} g P/yr. Mining phosphate for fertilizer adds some 15 x 10^{12} g P/yr to the land, although not all of this phosphorus may be transferred immediately to rivers.

Most of the phosphorus in rivers is insoluble and biologically unavailable, and there are major questions about the actual fraction of river-borne phosphorus that manages to participate in the biological cycle and the time scale for effective transfer of phosphorus from rivers to the oceans. The level of available phosphorus increases dramatically in the mixing zone between fresh river water and ocean waters. Most of this increase is presumed to be a result of desorption or dissolution of riverine phosphorus, but it may also partly arise from marine sources. Additional uncertainty is associated with storage of phosphorus in estuarine and coastal sediments. This issue is important since this phosphorus may be mobilized during epochs of low sea level (e.g., during glaciation), thereby potentially increasing marine biological activity in such epochs.

Uptake of phosphorus by organisms in the photic zone of the oceans is extremely rapid, and surface waters are typically highly depleted in mineral (soluble) phosphorus. However, nitrogen and phosphorus are present in the ocean in almost exactly the 16:1 ratio in which they are utilized by phytoplankton, and it is therefore difficult to tell whether marine productivity is limited by the availability of nitrogen or phosphorus. There is usually a small residual of soluble phosphorus present in upwelled waters after inorganic nitrogen has been exhausted, and hence the role of phosphorus is often assumed to be secondary. One puzzle is the absence of nitrogen fixation in this system. It has been argued that nitrogen fixation may be prevented by low levels of phosphorus, since nitrogen-fixing organisms appear to require high phosphorus levels. Thus marine cycles of nitrogen and phosphorus may be tightly coupled, making the human impact on the system more difficult to discern.

In the deep oceans the observation that PO_4^{3-} is roughly in equilibrium with the mineral apatite has been used to argue that this equilibrium controls the abundance of PO_4^{3-}. However, the chemical form of apatite in sediments is variable, and the time to establish equilibrium is very long. Phosphate in the oceans may instead be kinetically controlled by biological processes, but the basic mechanisms remain controversial. Similar uncertainty applies to the roles of biotic and abiotic processes in controlling availability of phosphorus in terrestrial soils.

Major problems concerning the phosphorus cycle on global scales may be summarized as follows: to identify the mechanisms controlling availability of phosphorus in terrestrial soils, and how these mechanisms respond to anthropogenic perturbations such as acid deposition, fire, or deforestation; to determine the magnitude of the flux of riverine phosphorus to the oceans and how the chemical availability of this phosphorus is controlled; and, finally, to determine if the productivity of the surface of the oceans is limited by phosphorus, in particular whether biological fixation of nitrogen would increase dramatically in coastal areas in response to anthropogenic enhancement of riverine phosphorus.

The Sulfur Cycle

Sulfur is an essential element in all living material, but unlike nitrogen and phosphorus it is rarely a limiting nutrient. Like nitrogen, sulfur exists in a variety of oxidation states, from -2 in sulfides to $+6$ in sulfates and is cycled among these states by the biota, volcanoes, combustion, and atmospheric reactions.

Gaseous sulfides (H_2S, OCS, $(CH_3)_2S$, CS_2) are emitted primarily as the result of biological processes in ocean surface water and in salt water and freshwater marshes. In particular, bacterial decay of organic material that contains sulfur in the -2 oxidation state can produce H_2S. Also, sulfur-reducing bacteria, which gain energy by oxidizing organic carbon to CO_2 using inorganic sulfate, can convert this sulfate to H_2S, $(CH_3)_2S$, CS_2, and OCS.

While fluxes of the long-lived gases OCS and CS_2 into the atmosphere are small, these gases travel large distances before oxidation and thus provide SO_2 and sulfate aerosol sources for the stratosphere. These gases are also by-products of coal conversion processes, and such anthropogenic contributions to OCS and CS_2 could be important because stratospheric sulfate aerosols influence the radiative budget of the Earth.

The influence of man on the sulfur cycle is far greater than his influence on either the carbon or nitrogen cycles. Combustion of fossil fuel is estimated to add twice as much gaseous sulfur to the atmosphere as the biota. Thus the anthropogenic influence dominates the global sulfur cycle. Even more important, combustion is concentrated in relatively few areas of the northern hemisphere, and the SO_2 produced from combustion is typically oxidized to sulfuric acid in a few days. Winds can carry SO_2 and sulfuric acid large distances (e.g., 1000 km) from their sources and deposit then in ecologically sensitive regions such as the North American and northern European forests, rivers, and lakes. Both SO_2 and sulfuric acid are harmful to plants, and the acid deposition (dry or wet) may dissolve and thus mobilize biologically harmful metals (aluminium and beryllium) in forest soils. Acid deposition derived from the combustion products SO_2 and NO_2 is now recognized as a major regional problem in the eastern United States and Canada and in Western Europe with serious implications for energy production from fossil fuels. The problem is exacerbated by the fact that NO_2 is an important species in determining O_3 and thus OH concentrations. In turn, OH is probably the major atmospheric oxidant for both NO_2 and SO_2.

For the sulfur cycle, there is a need to identify and quantify the anthropogenic and biological fluxes of reduced sulfur gases and determine whether these fluxes are subject to change. A far better understanding of the atmospheric chemistry of the reduced sulfur gases and the SO_2 from combustion is also needed. Of particular concern in this chemistry are the roles of heterogeneous reactions, the coupling to atmospheric nitrogen and carbon chemistry, and the mechanisms for dry and wet deposition. Finally, we require far more information on the manner in which sulfuric acid deposition affects the biology and geochemistry of terrestrial ecosystems.

SCIENTIFIC GOALS

The overall goals for the study of the global biogeochemical cycles address three general issues: (1) improved understanding of the oceanic, atmospheric, and biotic reservoirs per se, (2) improved understanding of the exchanges between these reservoirs, nd (3) prediction of changes important to the biosphere and climate.

The first goal for the study of global biogeochemical cycles is to determine the chemistry, physics, and biology of the important carbon, nitrogen, phosphorus, and sulfur compounds within the troposphere, within the oceans, and on the land. As outlined in the Introduction, there are large gaps in knowledge of the chemical behavior of the Earth's fluid media. Major efforts are needed, in particular in global oceanic and tropospheric chemistry and in the study of the biota.

The second goal is to determine and understand the mechanisms for the cycling of carbon, nitrogen, phosphorus, and sulfur between the troposphere, oceans, land, and biota. There is considerable need to better understand the processes of wet and dry deposition from the atmosphere, the role of the biota as sources and sinks for atmospheric and oceanic carbon, nitrogen, phosphorus, and sulfur compounds, and the manner in which rivers transport biologically important species from land to the oceans.

The third goal is to predict on time scales of decades to centuries the changes in the Earth's biogeochemistry that can affect climate, biological productivity, and human health. Of particular interest are changes in the abundances of the radiatively active gases (CO_2, N_2O, CH_4, and halocarbons) and aerosols, and changes in the concentrations and distributions of toxic substances including O_3, SO_2, and acidic particles.

Pursuit of these goals requires an extensive program of remote sensing in combination with intensive studies of selected systems. Observational programs will involve a combination of space-borne, air-borne, and surface measurements and must be complemented by appropriate modeling and laboratory investigations. Studies of the biota are inherently complex, requiring an interdisciplinary approach. Also, cooperation between experts in the chemical, physical, and biological areas is essential if progress is to be made.

SCIENTIFIC OBJECTIVES

The above goals are best approached through a series of specific objectives, which are themselves conveniently divided by reservoir: oceans, land, and atmosphere. This separation is purely for operational purposes; these components are linked tightly, as are the cycles of carbon, nitrogen, phosphorus, and sulfur.

OCEANS. The oceans play a central role in carbon and nutrient cycles. They contain more than 90 percent of the Earth's nonsedimentary carbon and nutrients, and they are hypothesized to remove at least half of the anthropogenic CO_2 added annually to the atmosphere. The oceans have enormous heat capacity, and they moderate fluctuations and latitudinal gradients of temperature important to global chemistry and biology.

Temporal and spatial variability is a regular feature of marine ecosystems. Heterogeneity in distributions and growth rates occurs at all scales, from seconds to decades and from millimeters to thousands of kilometers. The causes of biological heterogeneity are in large part a result of fluctuations in the physical processes of the ocean. As phytoplankton are largely at the mercy of water motions, their vertical and horizontal distributions will be generally determined by often incontinent movements of the oceans. These motions will affect distributions not only directly through transport but also indirectly by influencing nutrient and light supply rates. It is the variability of these processes in toto that results in biological fluctuations. A clear consequence is that studies of ocean productivity must be concerned with oceanic dynamics as well as biological processes.

It is particularly important to determine the rate of primary production, nitrogen fixation, denitrification, emanations of sulfur gases, the burial of organic debris, and the characteristics of the coupling of physical and chemical processes at the atmosphere-ocean boundary and the thermocline, which influence the availability of nutrients and affect the rate of photosynthesis in the upper mixed layer.

LAND. Historically, humans have established their civilizations and food chains by modifying existing terrestrial biomes. Usually the net result of these activities is ecological transformation driven by the continuous removal of biotic stocks. When humans conducted these activities in the preindustrial era, the magnitude of disturbance was generally small and the homeostasis of biomes was not affected. Today the Earth's population is both so large and so highly industrial that the need for biotic resources has required major exploitation of biomes. This has resulted in the disruption of the underlying biogeochemical cycles.

When a terrestrial biome is subjected to destructive disturbance, both organic matter and nutrients are lost to streamwater and/or to the atmosphere. These losses are due to a variety of factors, including higher soil temperatures, faster decomposition, lower primary production and plant nutrient uptake, and increased erosion. In land converted to agricultural use, the stocks of carbon, nitrogen, phosphorus, and sulfur often continue to decline for many years. More than half of the carbon and nitrogen present in native prairies or forests can be lost during the development of agricultural land. When disturbance is followed immediately by regrowth, organic matter and nutrient levels accumulate on site; material is added from the atmosphere by photosynthesis, nitrogen fixation, precipitation, and from rocks by weathering. As such, if immediate regrowth occurs, there is only a transient decrease in standing stock, which is followed by regeneration, often to former levels of biomass and nutrients. In contrast, changes that occur following permanent land clearing represent progressive changes to a new state characterized by lower biomass and less nutrients. Consequently, total nutrient and biomass content of a biome or vegetation class (and hence its biogeochemical source or sink strength) varies with the initial biome type, the time elapsed since disturbance, and the type of disturbance.

ATMOSPHERE. Trace gases in the troposphere are key components of the biogeochemical cycles of elements such as carbon, nitrogen, oxygen, sulfur, and halogens. The atmospheric concentration of a trace gas represents the net sum of sources, sinks, and transport, and the distribution of a gas provides valuable information concerning large-scale biogeochemical processes. Several tropospheric species play important roles in the transmission of solar and/or terrestrial radiation; in particular O_3, CH_4, N_2O, CO_2, halocarbons, and aerosols. These species are therefore significant components of the climate system. Minor species also control the chemistry of the atmosphere and in this capacity may become directly important in human affairs. Ozone and peroxides can injure forests and crops even at low concentrations, oxides of nitrogen and sulfur acidify precipitation with potential damage to vegetation, aquatic life, and buildings, and photochemical aerosols reduce visibility and affect human respiration.

The hydroxyl radical OH is a key reactant in the troposphere and may be subject to change as a result of human activity. A major removal mechanism for OH is reaction with CO. It is known that the principal sources of CO are combustion (burning of fossil fuels and biomass) and the atmospheric oxidation of methane, higher alkanes (C_2H_6, C_3H_8), and more complex biogenic hydrocarbons (e.g., isoprene and terpenes). The magnitudes of these sources, their distribution, or even their relative importance on a global scale are not known. Thus the recent history of CO in the atmosphere cannot be reconstructed, nor can its future course be projected. However, a perturbation in CO concentrations would have a major effect on the concentration of the OH radical and hence would affect a large suite of trace gases that are removed from the atmosphere by reaction with OH.

The committee has defined specific objectives for the study of the biogeochemistry of the oceans, land, and troposphere using earth-orbiting satellites. *The highest-priority primary objectives for the biogeochemistry of the oceans, land, and troposphere enunciated below are of equal importance. The committee emphasizes that attainment of the overall goals for the biogeochemical cycles will require measurements in addition to those possible from satellites.*

The primary objectives for the study of the biogeochemistry of the oceans from space are as follows, in order of priority:

1. *To measure the concentration of chlorophyll-a in the world's oceans.*

2. *To measure the rates of processes regulating removal of carbon, nitrogen, and phosphorus from surface waters in oceanic regions where intermediate and bottom waters are formed.* The required data sets are for (a) surface radiation and water turbidity, (b) precipitation, (c) extent of ice coverage, (d) atmospheric temperature and humidity, and (e) sea surface temperature and wind stress.

3. *To measure the rates of processes regulating removal of carbon, nitrogen, and phosphorus in regions of intense upwelling.* The required data sets are for (a) surface radiation and water turbidity, (b) sea surface temperature and wind stress, (c) atmospheric temperature and humidity, and (d) precipitation.

The primary objectives for the study of the biogeochemistry of the land from space are as follows, in order of priority:

1. *(a) To measure the areal extent and the change in areal extent of terrestrial biomes, and (b) To measure the biomass densities in the various terrestrial biomes.*

2. *To measure the rate of net primary production and respiration for the major biomes of the world including those in transitional or successional states.*

The primary objectives for the study of the chemistry of the troposphere from space are as follows, in order of priority:

1. *To measure the magnitudes of the terrestrial and oceanic sources and sinks for radiatively and chemically important tropospheric trace gases; in particular* CO_2, *CO*, CH_4 *and other hydrocarbons,* N_2O, NH_3, $(CH_3)_2S$, H_2S, *OCS, and* SO_2.

2. *To measure the atmospheric distributions, annual and latitudinal variations, and regionally and globally averaged long-term trends of chemically and radiatively important trace gases and aerosols, in particular* H_2O, *CO*, O_3, NO_2, SO_2, *and acidic or carbonaceous aerosols.*

The rationale and the measurement requirements for each of the above objectives are discussed below.

Oceans

Objective 1

To measure the concentration of chlorophyll-a in the world's oceans.

These measurements are required to deduce rates of primary production. It is necessary to differentiate between coastal zones, where productivity may be limited by sunlight, and areas of the open ocean, where supply of the nutrients nitrogen and phosphorus may be more important.

The temporal and spatial distributions of productivity and biomass at mesoscales and larger are particularly difficult to sample by ships. However, the intense variability of mesoscale features and their overlap with the locations and characteristic time and space scales of phytoplankton make them particularly important to ocean productivity. Key issues associated with the mapping of large-scale distributions of productivity and biomass are as follows:

1. Where are regions of high mesoscale variability?
2. How does mesoscale variability affect global productivity and biogeochemical cycling?
3. What is the global "climatology" of productivity and biomass, and how does it vary seasonally and interannually?
4. What is the vertical structure of biomass and productivity?

More than 80 percent of total plankton production occurs in waters beyond the limits of the continental shelves. The relatively small coastal and/or neritic region make up about 10 percent of the total ocean area and support the remaining 20 percent of the production. It is here that both coastal upwelling and the well-documented "spring bloom" phenomena of temperate latitudes occur. Neritic and nutrient-rich coastal waters are significantly more productive per unit area than those of the open ocean. The difference could potentially be even greater, but the open ocean has less seasonality in production and its euphotic zone is deeper. There are important differences in coastal and open ocean regions in the plankton types, in the means for delivery of nutrients, and in the fate of organic matter.

MEASUREMENT REQUIREMENTS. Mapping of near-surface chlorophyll-a can be accomplished by using an Ocean Color Imager in a sun-synchronous orbit providing daily global coverage with an equator crossing that is within 2 hours of local solar noon. Spatial resolution should be at least 1 km^2 in regions of high chlorophyll-a, but the measurement strategy should be flexible, allowing varied resolution appropriate to the spatial scales in color variation. In order to determine the composition of the phytoplankton biomass and to support more sophisticated routines to remove atmospheric and water turbidity effects, the instrument should be sensitive to wavelengths between 350 nm and 800 nm with a 10-nm resolution. The measurement objective is to establish oceanic primary production in near-surface waters to within ±30 percent, and perhaps more importantly, to reveal accurately the temporal and spatial variability and thereby provide insight into the underlying connections between oceanic primary production, nutrient cycling, and physical processes.

Objectives 2 and 3

To measure the rates of processes regulating removal of carbon, nitrogen, and phosphorus from surface waters in oceanic regions where intermediate and bottom waters are formed.

To measure the rates of processes regulating removal of carbon, nitrogen, and phosphorus in regions of intense upwelling.

To understand the observed temporal and spatial variability of primary production requires measurements of key physical processes and knowledge of their coupling to biological processes. The processes of bottom water formation and intense upwelling appear to provide not only a unique opportunity to uncover important relationships between physical and biological phenomena but also insight into specific important events that govern the broad aspects of the oceanic role in the cycling of carbon, nitrogen, sulfur, and phosphorus. Questions concerning the role of physical forcing are as follows:

1. What is the rate of bottom water formation, and how is primary production distributed in the areas of this formation?
2. What is the distribution of major nutrients?
3. What are the supply rates of nutrients from the deep ocean to the upper waters?
4. What is the rate of vertical mixing of the surface layer?
5. How do sunlight and winds affect biological processes?

It is necessary to emphasize that measurements of physical processes are essential for the understanding of biological processes in the oceans. Furthermore, understanding of the biological processes as well as the dynamics of the central biogeochemical elements in areas of bottom water formation and intense upwelling will require in-situ investigations of the water chemistry as well as its motion. From satellite observatories the most important achievable measurements relevant to the above objectives are those relating to the distribution in time and space of primary production, precipitation, temperature, wind, water turbidity, and sunlight in various oceanic regions, and to the determination of oceanic circulation. The observational requirements for these variables are covered in Chapter 8, which is devoted to climate, and in the discussion of the objectives for ocean dynamics that are addressed in Part I of the committee's strategy.

Land

Objective 1(a)

To measure the areal extent and the change in areal extent of terrestrial biomes.

Knowledge of the areal extent of different terrestrial biomes and the rate of change of terrestrial biomes is fundamental to an understanding of both biogeochemical cycling and changes in the Earth's energy budget and hydrological cycle that help determine climate. However, knowledge of the extent and rates of change in different terrestrial biomes is incomplete. Recent estimates of the clearing of closed canopy tropical forest for agriculture differ up to 200 percent. Boreal forests are estimated to represent approximately one-sixth of the total live organic carbon storage, yet worldwide estimates of the areas covered by boreal forests vary by more than 50 percent.

MEASUREMENT REQUIREMENTS. In order to carry out the measurements, the land area of the Earth should be divided into ecologically meaningful regions capable of study by remote sensing and appropriate to the issue of carbon and nutrient cycling, and the land use within each region must be established.

The committee is aware of one promising approach to land classification using climatological data (see Figure 7.3), which is based upon two assumptions: (1) temperature and moisture form an adequate statistical estimator of potential biomass, soil carbon, and nutrient stocks in most of the biomes of the Earth, and (2) these parameters can be sampled globally with sufficient accuracy and efficiency. If this classification proves appropriate, and/or if it can be complemented by necessary additional information such as soil type and quality, then a map of the potential terrestrial vegetation of the world should be developed at a scale of 50 km x 50 km. In order to do this, it will be necessary to extend meteorological data on annual average temperature and precipitation patterns to give a more uniform global coverage. This extension should provide an accuracy for mean annual temperature in degrees centigrade (excluding subzero periods) of ± 15 percent and an accuracy for average total annual precipitation of ±50 percent.

The task of establishing a map of actual vegetation is more difficult but still tractable. For instance, the total land area that supports

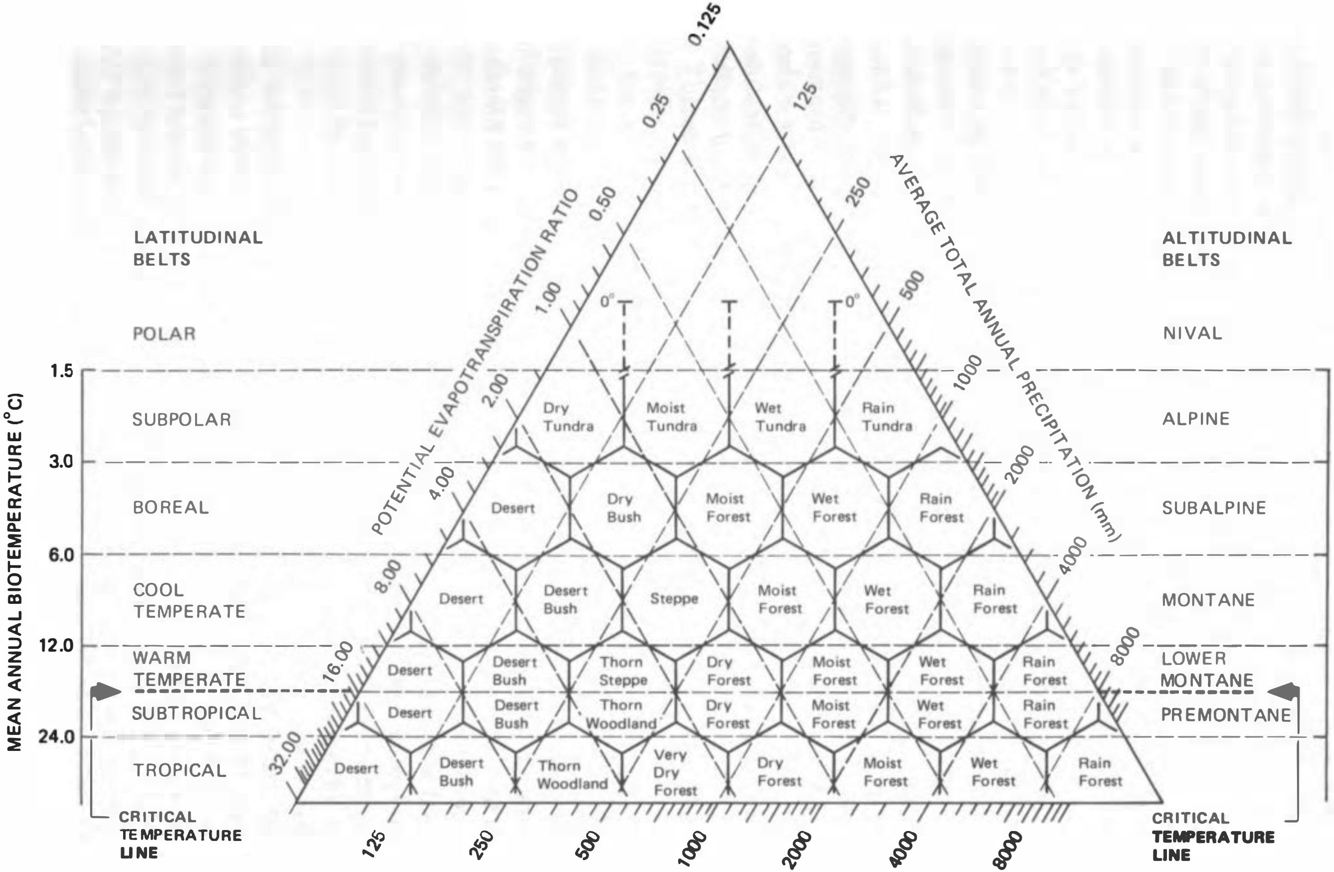


FIGURE 7.3 A biome classification scheme using temperature and moisture as estimators of biological activity.

vegetation is 147 x 10^6 km^2. A Landsat-3 scene covers about 22 x 10^3 km^2; worldwide coverage of land would require a minimum of 6.7 x 10^3 frames. A more realistic estimate is 12 x 10^3 frames, allowing for frames incorporating coastal waters and freshwater lakes. Cloud cover, equipment failures, difficulties in reception, and interrupted operation of satellites would likely double the total number of frames needed to 24 x 10^3. If changes in the vegetation are needed to establish a baseline rate, then the total would probably be doubled again to approximately 50 x 10^3 frames. On the other hand, once established, maps of the actual vegetative cover could be more easily updated by selective sampling to determine rates of land use change.

With respect to areal rate of the conversion of land from one biome (or land use) to another, the target accuracy is ± 10 percent. It should be stressed that this target applies to contemporary land use activities such as forest harvest, land clearing for agricultural purposes, urbanization, and abandonment of agricultural land and not to all changes in land cover such as the gradual and orderly natural development (succession) of a forest. It should be noted that there exist biome subclassifications that are consistent with the primary classifications shown in Figure 7.3 and are appropriate to the increased detail implicit in considering actual vegetation and contemporary land use data.

Objective 1(b)

To measure the biomass densities in the various terrestrial biomes.

While it appears that the ability to identify accurately changes in land use is in hand, acquiring the relevant information on the biomass within a biome—namely, the amount of biomass per unit area, the annual dynamics of this biomass, the change in this biomass following disturbance, and the interactions between carbon and other essential nutrients in both disturbed and undisturbed biomes—will require both new advances in satellite technology and implementation of in-situ measurement programs.

MEASUREMENT REQUIREMENTS. The method currently used for assessing biomass storage and potential productivity from remote sensing data is the measurement of leaf area index (LAI) of plant canopies, expressed as leaf upper surface area per unit land area (typical range is 0 to 20). In agricultural systems, it has been shown that water and CO_2 exchange by vegetation depends upon LAI, at least within a LAI range of 2 to 7. It remains to be shown, however, that with known LAI, forest type, and region, it is possible to determine biomass density or to infer net primary production. Certainly, if the total plant biomass is to be estimated, then it must be shown that the canopy geometry can be accurately inferred. It is likely that additional measurement in the microwave will be required. Certainly, it will be necessary to supplement visual data with radar in areas that are often cloud-covered.

Initially, LAI and biomass density should be explored in single-species tropical forests, boreal forests, climatically steep-gradient forests in the Pacific Northwest, deciduous forests in the eastern United States, savannas with a north-south gradient in tree density, and agricultural areas with a definite gradient in LAI. The objective is to establish biomass densities to within ±25 percent. If this measurement objective cannot be achieved using LAI, alternative approaches should be used, and at this time it appears reasonable that exploration of such alternative approaches should be emphasized.

Objective 2

To measure the rate of net primary production and respiration for the major biomes of the world including those in transitional or successional states.

The major difficulty with land classification schemes concerns identification of successional states. Succession is especially important in forests because of their large carbon and nutrient content. The ability to remotely detect successional communities will hinge on their spectral characteristics and the precision with which these characteristics can be measured from space.

A potentially fruitful new approach would be to infer biomass, successional state, net primary production, and respiration from biochemical characteristics of canopy leaves. This may possibly be done by measuring the reflectance or emissivity at several wavelengths (Figures 7.4 and 7.5 and Table 7.2). An anomalous signature detected in any one biome may be correlated with the presence of a new species, which, in turn, might allow the recognition of successional states or some emergent properties, such as a change in the overall biochemical quality of leaf tissue. This could be a key factor in determining rate of decomposition and nutrient cycling. Reflectance peaks in the infrared can be used to provide an indication of leaf water content, which, when coupled with measurements of canopy temperature, may provide indirect evidence concerning stomatal state. The stomatal state, when coupled with remotely sensed chlorophyll concentrations, might provide a basis for calculating net primary production. In addition, subtle absorption features occur in the IR that are related to cellular arrange-

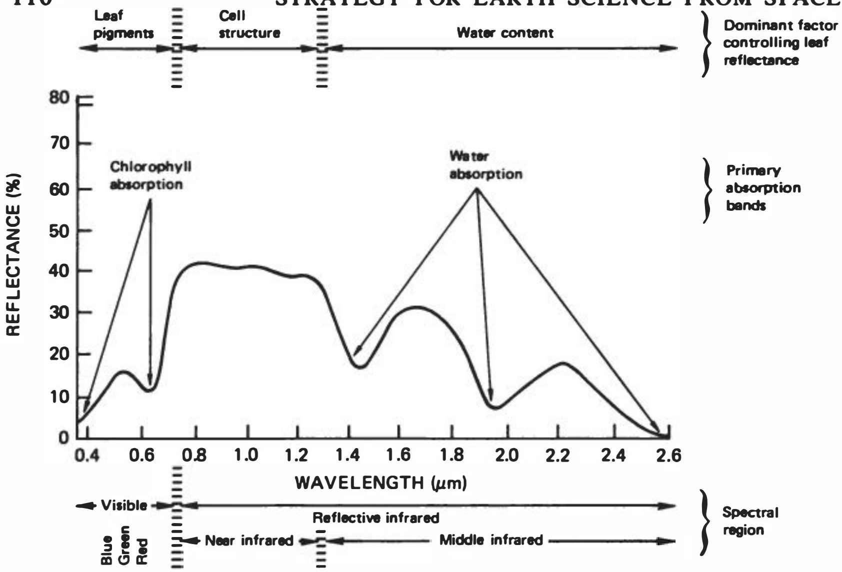


FIGURE 7.4 Typical plant reflectance as a function of wavelength.

ment within the leaf and to hydration state. Cellular arrangement within the leaf is genetically controlled and thus is of taxonomic significance. This raises the possibility for determining plant community composition to the genus and species level and hence successional state in some biomes (Figure 7.5).

MEASUREMENT REQUIREMENTS. In order to pursue this exploratory research issue of using more detailed spectral information, a series of test regions should be established where baseline measurements, both ground-based and remote, of carbon and nutrient stocks and fluxes could be developed. Simultaneously, the multispectral reflectance characteristics (see again Table 7.2 and Figure 7.4) of these regions should be explored to determine if the biochemical signature offered in the canopy leaves is of sufficient richness and strength to determine (1) biomass, (2) the flux of carbon and nutrients in these systems, particularly the rate of net primary production, (3) the species composition of the regions, and (4) the successional state of the region.

These test regions should again include boreal and tropical forests, savannas, and wetlands. Of course, any study of global biogeochemistry needs to consider temperate zone agriculture because large changes in the stocks of carbon, nitrogen, phosphorus, and sulfur occur when a system is subjected to continuous cultivation, but, in addition, industrial agriculture requires large anthropogenic inputs of water,

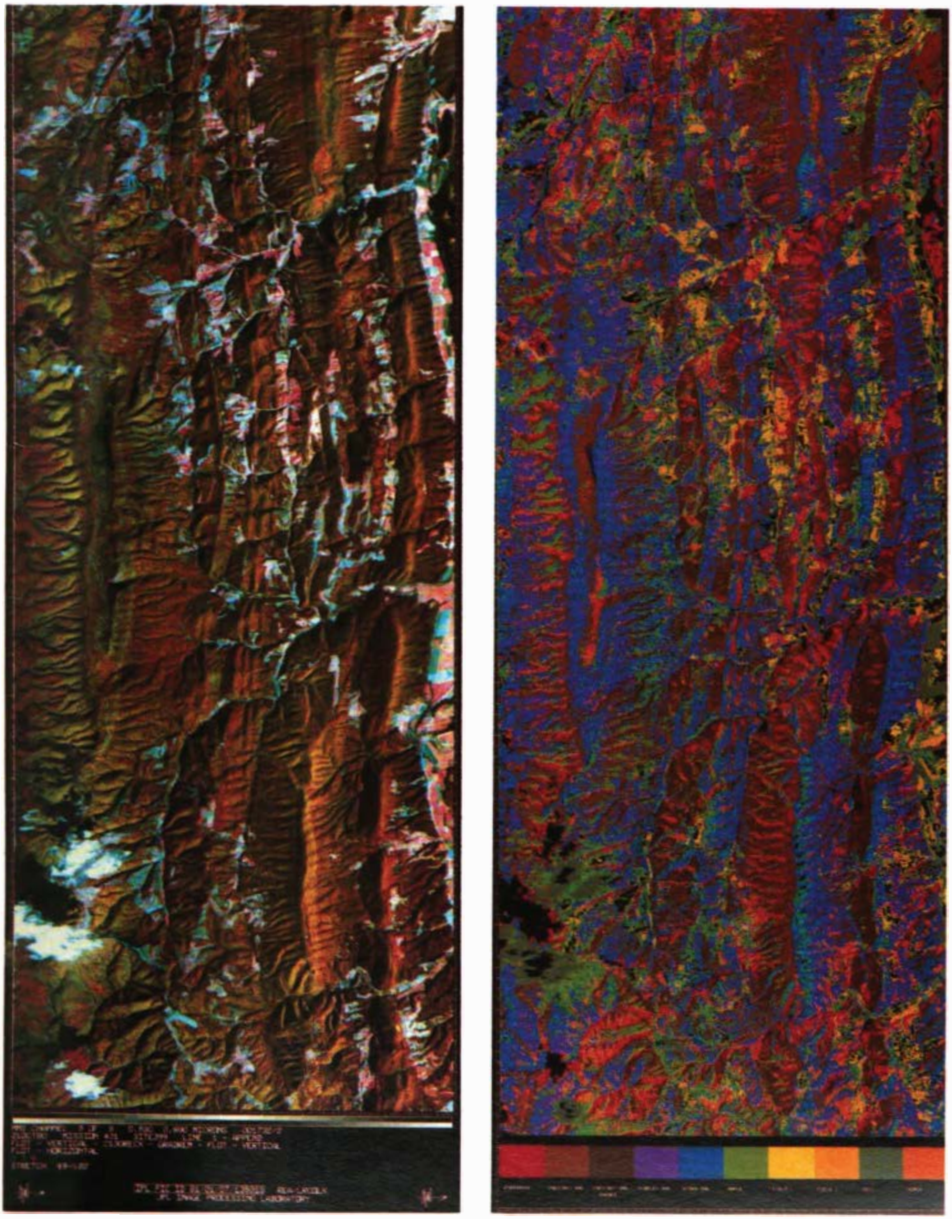


FIGURE 7.5 Mapping of deciduous forest cover using observations from aircraft that simulate Landsat-4 Thematic Mapper spatial and spectral resolution.

TABLE 7.2 Fine Structure of Plant Spectra in the Infrared

Approximate Wavelength (μm)	Type of Feature	Value
0.45	Absorption	Detection of changes in chlorophyll to carotenoid ratio (related to stress).
0.68	Absorption	Detection of chlorophyll, and tannin and anthocyanin content (initial stress detection).
0.75	Reflectance	Senescence detection (dead or dormant vegetation).
0.80	Absorption	Possibly related to leaf anatomy and/or state of hydration.
0.88	Reflectance	Height of feature may be useful in species discrimination.
0.96	Absorption	Shifts in this minor water absorption band may be useful in species discrimination and determination of hydration state.
1.0	Reflectance	Shifts in peaks may be related to leaf anatomy and/or morphology. May be useful in species discrimination.
1.2	Absorption	Shifts in this minor water absorption band may be useful in species discrimination and determination of hydration state.
1.3	Reflectance	Height of this feature useful for species discrimination of senescent forest species. A ratio of this feature with the one at 1.6 μm offers a good indication of moisture content and thus stress.
1.6	Reflectance	An indicator of moisture content of the leaf. It may also be an indicator of variation in leaf anatomy, and possibly useful for species discrimination.
2.2	Reflectance	An indicator of moisture content and may be useful for species discrimination.
3-5 and 8-14	Emission	Little is known concerning the value of thermal IR data in the study of vegetation. This is an area that needs further study.

nitrogen, phosphorus, and sulfur. Fortunately, there is an extensive data base on carbon and nutrient stocks on which to create an understanding of industrial temperate zone agriculture in its global context, and in particular, its relationship to the biogeochemical and climate systems of the planet.

In contrast, the densities and fluxes of carbon and major nutrients

TABLE 7.3 Space-borne Measurement Requirements for Terrestrial Vegetation

Scientific Issue	Candidate Spectral Band(s)	Temporal Scale	Spatial Resolution
1. *Biome classification*			
Evapotranspiration	Visible-near IR	Daily }	30 m (test sites), 0.5 km to 1 km (elsewhere)
Precipitation	Microwave	Daily }	
Temperature	Thermal infrared	Twice weekly	1 km
2. *Rate of land conversion*	Visible-near IR	Annual	30 m (selective sampling)
3. *Density*			
Biomass and geometric structure	Visible-near IR	Monthly	30 m (test sites), 0.5 to 1 km (elsewhere)
Primary production	Visible-near IR	Weekly	30 m (test sites), 0.5 to 1 km (elsewhere)

in tropical and boreal forests are described poorly in available data. The rates of disturbance in tropical forests are large, and the responses of these systems to repeated harvest are not well understood. There exist tropical forest research stations in many areas, including the Ivory Coast, Venezuela, and Costa Rica. The La Selva site in Costa Rica offers the advantages of a long-term research site with substantial reserved land in a region that is developing rapidly; this makes it a particularly appropriate site for developing a remote sensing technique to evaluate long-term tropical forest land use change.

Savanna biomes are characterized by a mixture of grass and woody vegetation. They occur predominantly in the tropics, occupying those regions between the arid deserts and the moist woodlands. They are significant in that they exhibit marked natural fluctuations in productivity, up to 500 percent between seasons, and they are currently being subjected to large anthropogenic changes. Wetlands are a major natural source of reduced trace gases in the troposphere, and it is believed that worldwide wetlands are being lost at a rapid rate through conversion to agriculture.

Table 7.3 summarizes both the satellite-borne global terrestrial observations as well as the test site observations that are essential to the land-related objectives.

Atmosphere

Objective 1

To measure the magnitudes of the terrestrial and oceanic sources and sinks for radiatively and chemically important tropospheric trace gases.

The trace gases of greatest importance are CO_2, CO, CH_4 and other abundant light hydrocarbons, N_2O, NH_3, $(CH_3)_2S$, H_2S, OCS, and SO_2. To address this objective, both satellite and in-situ (ground-based, aircraft) measurements are required. Satellite observations are required to determine the areal extents, global distributions, and climatologies of the important trace-gas-emitting biomes or regions (e.g., marshes, tundra, oceanic microorganisms, and urban area). Satellites can also provide direct observations of some emitted species (e.g. CO). In-situ measurements are required to determine the fluxes of the various trace gases from the relevant biomes or regions as functions of the important climatic and related variables (e.g., temperature, sunlight, moisture, and human activity). Combination of these two data sets with areal extent of each region will yield the required estimates of global surface emissions.

The major surface sink for trace gases or for their alteration products (gases, aerosols) is dry and/or wet deposition. The most significant contribution which satellites can make to our understanding of these important sinks is to provide a global picture of cloud and aerosol distributions and of precipitation rates.

MEASUREMENT REQUIREMENTS. Measurement details for terrestrial biomes have been discussed under land Objectives 1(a) and 1(b) in this chapter. For the oceanic biomes, the mapping of chlorophyll-a and the measurement of nutrient fluxes in downwelling and upwelling regions are also relevant and are discussed under ocean Objectives 1, 2, and 3 in this chapter. However, the committee emphasizes that the biomes relevant to trace gas emission differ in general from those relevant to overall primary production. In many cases, in-situ studies will be necessary to identify the gas-emitting biomes, and this must, of course, precede analysis of satellite data.

For precipitation, the measurement requirements are essentially the same as those defined in Chapter 6 for the global hydrologic cycle. For clouds and aerosols the requirements are the same as those for climate change and prediction defined in Chapter 8. Other climate-defining parameters (temperature, soil moisture, sunlight, etc.) are discussed in Chapter 4 for the troposphere; the measurement requirements defined there are more than adequate for use in defining bioclimates.

Objective 2

To measure the atmospheric distributions, annual and latitudinal variations, and regionally and globally averaged long-term trends of chemically and radiatively important trace gases and aerosols.

The trace species of greatest importance are the precursor and/or product gases (H_2O, CO, CH_4 and other abundant hydrocarbons, N_2O, NH_3, $(CH_3)_2S$, H_2S, OCS, SO_2, HCl, abundant chlorocarbons and chlorofluorocarbons); the photochemically active gases (O_3 and NO_2); and the chemically produced aerosols (sulfate, nitrate, and organics). Many of these species exhibit significant variations with longitude, latitude, altitude, and season. These inhomogeneities provide an essential link between sources and sinks, internal chemistry, and transport in the troposphere. For example, differences in concentration of chlorofluoromethanes between the hemispheres may be used to determine interhemispheric exchange times and to check on the validity of global circulation models.

For trace gases with tropospheric lifetimes far exceeding pole-to-pole transport times (e.g., $CFCl_3$, CF_2Cl_2, and N_2O), both their tropospheric distributions and long-term trends can be effectively measured at the surface. For species with lifetimes far exceeding the surface-to-tropopause transport times (e.g., CH_4, CH_3CCl_3, and OCS), surface measurements can also provide essential information, particularly on long-term trends. In the near term, these and other long-lived species are best investigated in the troposphere through a combination of aircraft measurements (for distributions) and ground station measurements (for trends). The committee emphasizes that many of these gases have *short* lifetimes in the stratosphere and a very different measurement strategy applies there (see Chapter 5). The principal removal mechanism for tropospheric CH_3CCl_3 is reaction with OH, so measurements of the concentration and long-term trend for this species provides a potentially accurate determination of the global tropospheric-average OH concentration.

On the other hand, for short-lived species that are highly variable in space and/or time (e.g., H_2O, O_3, NO_2, SO_2, CO, and aerosols), definition of the distribution and long-term trend is hampered by the difficulty in determining the vertical distribution from ground stations. Determination of the global distribution from space thus offers a powerful complement to data gathered from baseline stations.

TABLE 7.4 Tropospheric Trace Gas Measurements from Satellites

Gas	Concentration (V/V)	Status	Remarks
First Level			
H_2O	0.005-0.04	*	Upper troposphere of special interest.
O_3	40-100 ppb	2	Laser?
CO	0.05-0.3 ppm	*	Gas filter radiometer?
CH_4	1.7 ppm	1	High-resolution spectrometer, gas filter radiometer?
Second Level			
N_2O	0.3 ppm	1	High-resolution spectrometer, gas filter radiometer; high precision needed for measurement of trend?
NO_2	0.01-10 ppb	1	Urban plumes probable, UV absorption?
NH_3	0.1-1 ppb	2	IR spectrometer?
SO_2	0.05-1 ppb	1	UV absorption or fluorescence, urban plumes probable.
Chlorofluoromethanes	0.2 ppb	1	Gas filter radiometer, high-resolution spectrometer?
HC1	0.1-1 ppb	1	Near IR spectrometer?

* Feasible today.
1 Probably feasible.
2 Possible.

Development of satellite remote sensing sounding techniques for trace gases in the troposphere, however, has received relatively little attention compared with higher regions of the atmosphere. It is clear, however, that enormous potential exists for such measurements. Table 7.4 summarizes gases that are targets for study from space. Those listed as first-level species are major trace gases, with concentrations exceeding 0.1 ppm (except O_3). They are also of the greatest interest for initial studies. Some gases could be studied from space in a relatively short period of time, since techniques for measurement exist. In the latter category are the first-level gases, water vapor and CO. The distribution of water vapor plays a major role in atmospheric chemistry, since H_2O is the precursor of OH radicals, but the concentration of water vapor in the middle and upper troposphere is not sufficiently well known (particularly for mixing ratios below 10^{-3}). Similar uncertainty exists for CO, which is the major sink for OH radicals.

Species listed on the second level include some key reactive constituents, such as NO_2. Measurement of these compounds from space is, in general, more difficult than measurement of species on the first level, but there are promising avenues. For example, NO_2 may be observed using UV absorption, at least for regions such as urban plumes where concentrations are high.

It may be surprising at first that tropospheric measurements from space are not more advanced. Most of the required remote measurements are optical, and consequently the prevalence of clouds and aerosols renders the task difficult. Limb-viewing measurements may be expected to succeed only 10 percent of the time in the tropics, and 25 to 50 percent of the time in higher latitudes. Nadir-viewing instruments should see into the troposphere more often than limb-viewing instruments, but the high pressures of the troposphere broaden spectral lines, making altitude resolution difficult. Tropospheric H_2O and CO_2 blanket much of the useful spectrum, and the large abundances of O_3 and NO_2 in the stratosphere may conceal tropospheric constituents from view. It would appear that these difficulties can be overcome and may, in some cases, be turned into advantages. To avoid clouds, an experimenter may be forced to use a nadir-viewing instrument with a small field of view, a directional scan capability, and on-board data processing to permit rejection of significant quantities of data. Although difficult to build, such an instrument might prove to be unusually flexible and able to examine both regional and global-scale phenomena. Similarly, pressure-broadened lines may allow observation of tropospheric species below a stratospheric overburden.

In summary, the space observatory needed to address this objective should have global coverage insofar as possible: near-polar orbit, with limb or nadir view. Occultation measurements do not provide a global picture of the sort desired to address the principal objectives. Most of the important areas of research require an extended mission of months or years duration, almost always with coordinated ground truth or in-situ measurements. Critical in-situ measurements are (1) ground-based and aircraft measurements of important gases and radicals with particular emphasis on OH, (2) field experiments to elucidate mechanisms and strengths of surface sources and sinks, and (3) measurements at "baseline" stations in remote areas to determine long-term global trends of chemically and radiatively important long-lived species. The committee is aware of a detailed strategy for the study of global tropospheric chemistry addressing in-situ measurements (*Global Tropospheric Chemistry: 1. A Plan for Action; 2. Current Assessment*, National Academy Press, 1984). *The committee emphasizes that the space-based strategy for tropospheric chemistry presented here must be accompanied by a complementary program of in-situ measurements.*

ADVANCES IN THEORY AND MODELING

The most advanced work in modeling biogeochemical cycles to date has dealt with the carbon cycle. Until recently, these models have employed relatively simple causalities with nonlinearity entering only to treat the carbonate system in the oceans and possible CO_2 stimulation of terrestrial vegetation. Interactions among the biogeochemical cycles have not been adequately addressed. In addition, even these models have been oversimplified by using a comparatively small number of global-scale well-mixed reservoirs. Consequently, it is difficult to be consistently accurate, because in reality the crucial physical and chemical processes correspond to such large time and space averages. It is clear that results obtained with such a crude representation of the global system, using only a few reservoirs described by first-order processes, are to be considered only as zero-order estimates of natural processes. The inadequacy of such models has been obvious as, for example, in the attempt to use them to investigate the role of the oceans or terrestrial biomes in the global carbon cycle.

Future progress will require the explicit consideration of spatial heterogeneity. To adequately describe the terrestrial ecosystem of the world and its alteration by humans, we need to consider areal scales of the order of 50 km x 50 km. Physically, chemically, biologically, dynamically, and spatially distinct regions of the world's oceans also will need separate consideration. This will require methodologies that are appropriate for studying systems with hundreds of boxes or grid points as well as techniques for extracting consistent information from diverse global data sets. The existence of data and the use of data are fundamental to future progress; for example, higher resolution oceanic models must be built on extensive sets of consistent oceanographic data.

In the future, studies of the circulation of the oceans are expected to be pursued (as they are currently) along two complementary paths of investigation. One is to exploit the distribution of tracers, both chemical and physical, to infer the dynamical processes of the oceans. When tracers are biologically mediated, this approach explicitly considers the interaction between physical and biological processes since the biota of the sea can act as significant sources and/or sinks for chemical species. Currently, advances in mathematical inverse techniques combined with additional chemical and physical tracer data offer the possibility of a viable tracer circulation model for the oceans. However, the clarification by satellite and other means of the boundary conditions and constraints that arise from surface dynamics, such as precipitation, evaporation, temperature, and net primary production, is needed for the successful development of these models.

The second approach is directed toward determining the general circulation of the oceans from the wind stress at the surface of the sea, from the exchange of heat with the overlying atmosphere, and generally from sea surface topography. This approach will require a combination of remote sensing devices (a scatterometer to obtain wind stress and a high-resolution altimeter for ocean topography) in conjunction with in-situ measurement techniques (acoustic tomography and acoustic ship-board current meters) and long-term monitoring of *both* chemical and physical variables. It has been discussed extensively in Part I of the committee's strategy.

Within the land biota reservoir, a major initial advance in our understanding of the role of terrestrial biomes in the Earth's biogeochemistry will come simply from mapping land use, and ecosystem type and state, in a geographical context that considers explicitly spatial heterogeneity at 50-km resolution and at least seasonal temporal detail. Beyond this and of equal importance will be the development of conceptually clear models of the global cycles that include an initial state, alterations by humans, and the effects of interactions among the cycles. Any elaborate field study should be preceded by the development of a hierarchy of models of increasing sophistication to formulate properly the value of and the needed accuracy for in-situ experiments.

In the area of tropospheric chemistry the studies of the sources, sinks, and global distributions of chemically and radiatively important species discussed earlier must be augmented by studies of chemical interactions among these species. The chemical interactions among tropospheric species have been a major concern over the past few years, with O_3 and the hydroxyl radical OH playing central roles. Photolysis of O_3 initiates the chain reactions that produce critically influential labile species such as OH, peroxides, and strong acids (HNO_3 and H_2SO_4). In order to better determine the dynamics of these interactions, major questions need to be answered. How much O_3 is produced in the perturbed plumes from industrial areas? What is the ultraviolet radiation environment that initiates radical photochemistry? How does the transport of nitrogen and sulfur oxides from urban areas influence global tropospheric chemistry?

To address the sources, sinks, distributions, interactions, and transport of tropospheric species, the space-borne measurements must be accompanied by (1) laboratory measurements of reaction rates, aerosol optical and chemical properties, and biological metabolic processes, and (2) theoretical studies of global-scale coupled transport and chemistry.

Such unified, carefully designed research efforts should produce major advances in our ability to assess important questions about the biogeochemistry of the Earth. In this light, *the committee emphasizes that laboratory and theoretical investigations are essential to the success of its space-based strategy for the biogeochemical cycles.*

ADVANCES IN INSTRUMENTATION

The critical developments needed in space-based instrumentation for the biogeochemical cycles relate to the required measurements for precipitation, chlorophyll-a, tropospheric trace gases (H_2O, O_3, CO, NO_2, and SO_2), and net primary production. Precipitation instrumentation is addressed elsewhere in this report (Chapter 4). For chlorophyll-a, improvements are needed in discerning accurately the separate contributions of atmospheric aerosols and the ocean surface to the observed spectrum. For the trace gases, some suggested approaches were mentioned above; these and other promising techniques should be carefully investigated and tested. For net primary production we need a much better understanding of the relationship between the state of vegetation and its reflection spectrum in order to design a suitable multispectral instrument to address this important topic.

For in-situ measurements, critical developments are needed in techniques for measurements of trace gas fluxes from biomes. We also need development of instruments for accurate determination of OH radical concentrations; the specific committee recommendation for this latter species is given in Chapter 5.

8
Goals and Objectives for Study and Prediction of Long-Term Climatic Changes

INTRODUCTION

Reconstruction of past climate from geological, proxy, ice core, and instrumental records reveals that significant continental- to global-scale changes have occurred on several time scales: the 100,000-year glacial-interglacial oscillation of the Pleistocene epoch; the little ice age between the mid-fifteenth and the mid-nineteenth century, when northern hemisphere winter temperatures were significantly colder than today; and the apparent variations of about 0.5 to 1 K in hemispherical mean temperatures during the last 100 years. Important changes have also occurred on regional scales: the significant advance of glaciers in the European Alps and New Zealand during the little ice age; the severe drought during the 1930's in the south central United States (dust bowl); and the Sahel drought between 1968 and 1973, among several others. As yet, we have only plausibility arguments and hypotheses, which are difficult to verify owing to data limitations, to explain most of the observed climate changes. The suggested explanations have involved both physical (e.g., changes in the solar constant) and biological (e.g., changes in global rate of photosynthesis) processes.

In the last two decades, significant progress has been made in modeling the global climate system and in the acquisition of global data sets for temperature, wind, humidity, and the radiation budget. The models, in conjunction with the data, have enabled quantitative albeit proxy tests of numerous theories of climate change and identification of the important climate forcing functions as well as the feedback processes that govern the response of the climate system.

The most sophisticated models indicate that during the next several decades human activities have the potential for altering the current climate. In particular, these models estimate that by the end of this century, the global warming due to anthropogenic increases in CO_2 and other radiatively active trace gases (see Figures 7.1 and 8.1) will exceed the "natural" variations. The models also predict that unprecedented warming will be accompanied by a more vigorous hydrological cycle and a decrease in the polar sea ice and snow cover.

Several regional climate forcing terms are also being altered by human activities. The alteration of land use patterns is an important example. Deforestation and the subsequent exposure of the underlying soil alters the albedo and the evapotranspiration of the surface, both of which play an important role in determining the soil moisture and its temperature. The presence of industrial aerosols in the troposphere modulates the longwave and solar fluxes to the surface-troposphere system. More recently, it has also been suggested that carbonaceous aerosols detected in the arctic may have an appreciable impact on the arctic radiative energy budget.

The potential long-term (decadal to century) global and regional climate changes due to human activities should be viewed within the context of natural variations in the climate system that are forced "externally" (solar insolation, volcanic eruptions, evolution of vegetation, deliberate deforestation, to name a few) and/or can result from unforced variations in the "internal" parameters (for example, sea surface temperatures, upper ocean heat storage, vegetative cover, and sea ice). A more complete list of natural and anthropogenic factors influencing long-term climate change is given in Table 8.1(a). The variations in climate that are forced externally, either by natural causes (e.g., volcanic activity) or by anthropogenic sources (e.g., deforestation), are denoted as external variations in Table 8.1(a). The natural variations in internal climate parameters can, in some instances, be considered as variations in climate forcing terms. For example, long-term change in ice cover can drastically alter the absorbed solar radiation and the polar ocean-atmosphere exchange of sensible heat (if sea ice changes). Note also that the biota can act as both an internal and external forcing mechanism. For example, the evolution of the first photosynthetic organisms would be an external forcing, whereas changes in vegetation cover resulting from climate changes would be an internal forcing.

The discussion, so far, implicitly adopted the most general definition

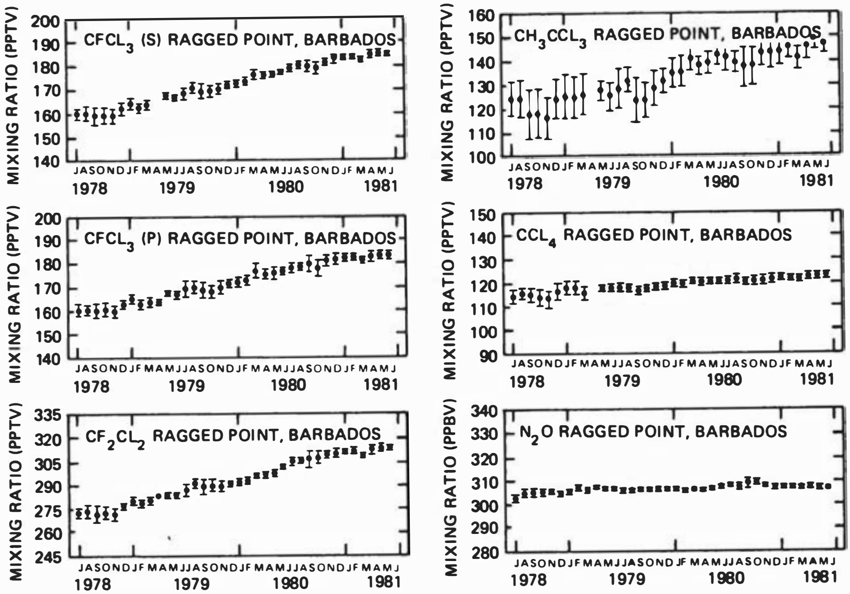


FIGURE 8.1(a) Trends for $CFCl_3$, CF_2Cl_2, CH_3CCl_3, CCl_4, and N_2O measured at Ragged Point, Barbados (13°N, 59°W).

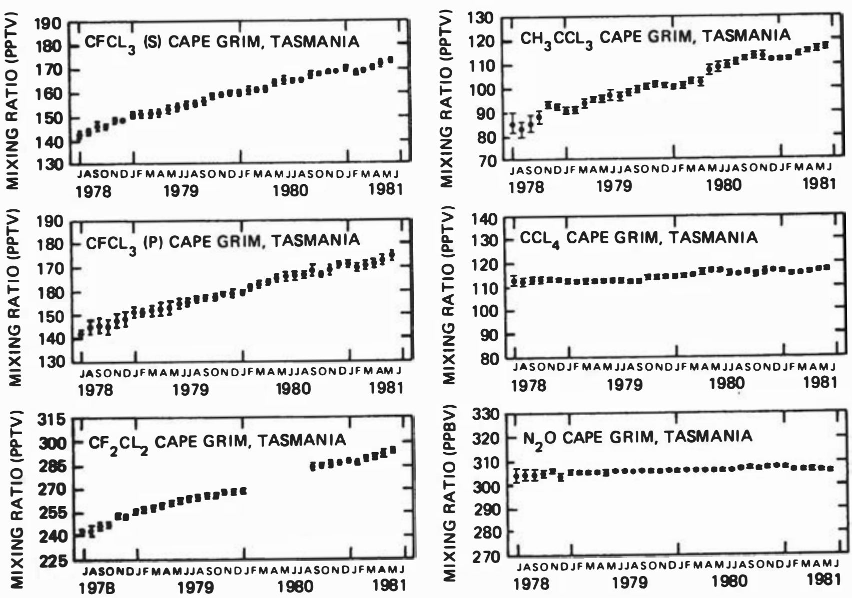


FIGURE 8.1(b) Trends for $CFCl_3$, CF_2Cl_2, CH_3CCl_3, CCl_4, and N_2O measured at Cape Grim, Tasmania (41°S, 145°E).

of climate (also see Chapter 4), which includes both the state of the atmosphere-land-ocean-biota system averaged over a time scale of several weeks and its variation over seasonal to longer time scales. The goals and objectives for understanding seasonal to interannual variations have been described in Chapter 4. Climate variations on decadal to longer time scales will be the focus of this chapter. Progress toward a better understanding of the causes of the past climate changes and toward prediction of the future long-term trends in global and regional climate is severely hampered by several factors:

1. The first is the existence of the simultaneous variations in several forcing terms of natural and anthropogenic origin, which make it difficult to distinguish individual causes and effects. For example, consider the last 50-year period. The observed increase in CO_2 should have enhanced the radiative heating of the surface-troposphere system. Large volcanic eruptions, particularly those of Agung in 1964 and El Chichon in 1982, whose effects linger for several years, have reduced the solar radiation reaching the surface and, at the same time, enhanced the stratospheric longwave opacity. Anthropogenic activity has demonstrably contributed to tropospheric turbidity, which has a substantial effect on both the solar and the longwave heating of the troposphere. The clearing of vegetation should have enhanced the visible albedo of the surface, changed the surface emissivity in the 8- to 12-μm region, and altered the evapotranspiration from the surface. Each of the above changes has about the same order of magnitude contribution to the perturbation in the regional energy budget, thus making it extremely difficult to identify the causes for the observed climate change.

2. The second factor is that despite recent significant refinements, major problems remain in climate theory and modeling. These problems concern the role of interactive feedback processes involving the atmosphere, oceans, biosphere, and cryosphere. In principle, we can identify a myriad of feedback processes involving the above components of climate system. Cloud feedback ranks highest in priority not only because of its importance to the climate sensitivity question but also because the role of cloud feedback in determining the sensitivity of global and regional climate to radiative forcing is still a mystery. The potential importance of the cloud feedback has been emphasized in a number of theoretical studies. In particular, it can easily be shown that the model-estimated surface warming due to a doubling of CO_2 can be completely compensated by a mere 2 to 4 percent increase in the amount of low-level clouds. Likewise, a corresponding decrease in these clouds can amplify the CO_2 warming by a factor of 2 or more.

As yet, we do not have any precise understanding of how cloud cover, cloud heights, and cloud optics will respond to a change in regional and global surface properties or a change in tropospheric temperatures. A major reason for the slow progress in this area is that several of the key interactive processes occur on spatial scales of the order of 10 to 100 km, which are not resolved in theoretical models. These "subgrid scale" processes include, among others, cloud maintenance, precipitation, boundary layer energy transfer, and evapotranspiration from plant canopies.

Another major source of uncertainty is the role of the world's oceans in determining time lags in the response of the climate system to a particular forcing. On decadal time scales, this time lag is largely governed by the depth of the mixed layer and the rate of exchange of thermal energy between the mixed layer and the thermocline. The mixed layer depth undergoes strong seasonal, latitudinal and longitudinal variations from several tens of meters in parts of the tropical oceans to several hundred meters in the polar winter oceans. Current state-of-the-art climate models largely ignore such variations. The ocean surface currents and mesoscale eddies, together with the mixed layer and its exchange of energy with the atmosphere above and the water below, are both components of the climate system that have to be properly included in our models when dealing with decadal climate changes. Unfortunately, our current understanding of these global-scale components is derived largely from data of unknown quality with insufficient temporal and spatial sampling. For example, because of sampling and instrumental biases, the sea surface temperatures are not known to better than 1 to 2 K.

3. The third factor to consider is the presence of interactions between climate and chemistry which involve radiatively active minor trace gases. One of the interesting developments in recent years is the perceived importance of the minor trace gases other than CO_2 (see Table 8.1(b) and Figure 8.1) in enhancing the atmospheric greenhouse effect. Since the minor trace gases absorb radiation in the 8- to 12-μm region, where the background atmosphere is highly transparent, and since the radiative warming due to these gases increases linearly with their concentration, adding one molecule of $CFCl_3$ or CF_2Cl_2 is predicted to have roughly the same surface warming effect as adding 10^4 molecules of CO_2 to the atmosphere. By most theoretical estimates, the collective surface warming effect due to expected increases in the minor trace gases in Table 8.1(b) is predicted to be as large as that due to the expected CO_2 increase. However, the minor trace gases problem is more complicated than the CO_2 problem since the overall effects of

TABLE 8.1(a) Parameters Influencing Decadal and Longer Climate Change

	Forcing Mechanism[a]
External Variations	
Natural	
Solar irradiance	R and photochemical
Aerosols (volcanic)	R (S and LW)
Vegetation	R, evapotranspiration, and photosynthesis
Anthropogenic	
CO_2	R (LW)
Ozone and other minor trace gases	See Table 8.1(b)
Vegetation	R, evapotranspiration, and photosynthesis
Aerosols (soot and other tropospheric)	R (S and LW)
Albedo of polar snow and sea ice	R (S)
Waste heat	R (LW) and sensible heat
Clouds (aerosol nucleation)	R (S and LW)
Cirrus clouds (jet contrails)	R (S and LW)
Internal Variations	
Sea surface temperature	Release of latent heat
Sea ice and snow cover	R and release of sensible heat
Clouds	R and latent heat
Tropospheric and stratospheric water vapor	R (LW)
Soil moisture	Evaporation
Vegetation	R, evapotranspiration, and photosynthesis

[a] R = radiative; S = solar; LW = longwave radiation.

these gases depend on the following processes: (a) Chemically active trace gases can perturb radiatively active gases. For example, anthropogenic addition of CO and NO (which have negligible radiative effects) can perturb tropospheric ozone, which has a substantial radiative effect on surface and tropospheric temperatures; (b) The minor trace gas effects depend on stratosphere-troposphere interactions. For example, the depletion of stratospheric ozone due to chlorofluoromethanes can influence tropospheric temperatures since ozone modulates the solar and longwave radiation incident on the surface and troposphere; (c) Changes in tropospheric H_2O, for example due to tropospheric warming, can alter the tropospheric chemistry. By most model estimates, the warming due to CO_2 doubling would enhance the tropospheric H_2O content by 15 to 30 percent.

The committee outlines here a long-term measurement strategy

TABLE 8.1(b) Radiatively Active Minor Trace Gases in the Atmosphere

Trace Gas	Chemical Symbol
Carbon Group	
Carbon dioxide	CO_2
Methane	CH_4
Oxygen Group	
Ozone	O_3
Nitrogen Group	
Nitrous oxide	N_2O
Nitrogen dioxide	NO_2
Dinitrogen pentoxide	N_2O_5
Nitric acid	HNO_3
Ammonia	NH_3
Sulfur Group	
Sulfur dioxide	SO_2
Carbonyl sulfide	COS
Carbon disulfide	CS_2
Halogen Group	
Trichlorofluoromethane (CFC11)	$CFCl_3$
Dichlorodifluoromethane (CFC12)	CF_2Cl_2
Chlorotrifluoromethane (CFC13)	CF_3Cl
Dichlorofluoromethane (CFC21)	$CFHCl_2$
Trichlorotrifluoroethane (CFC113)	CF_3CCl_3
Dichlorotetrafluoroethane (CFC114)	$C_2F_4Cl_2$
Chloropentafluoroethane (CFC115)	C_2F_5Cl
Hexafluoroethane (CFC116)	C_2F_6
Carbon tetrachloride	CCl_4
Methyl bromide	CH_3Br
Methyl chloride	CH_3Cl
Carbon tetrafluoride	CF_4
Methylene chloride	CH_2Cl_2
Tetrachloroethylene	C_2Cl_4
Nonmethane Hydrocarbons	
Acetylene	C_2H_2
Ethylene	C_2H_4
Ethane	C_2H_6
Propane	C_3H_8
Benzene	C_6H_6
Others	
Peroxyacetyl nitrate	$CH_3(CO)O_2NO_2$

aimed at addressing and unraveling the key issues of the climate problem. This strategy is guided by scientific considerations. However, the strategy also offers immense practical benefits. For example, the proposed measurements will quantify the magnitude and sign of the various climate forcing terms and their variations due to natural and anthropogenic factors. Such estimates, because of the inherent time lags in the response of the system imposed by the inertia of the oceans, provide a measure of the future climate changes. Furthermore, these measurements will provide sufficient insights to evaluate the potential effects of continuing trends in various human activities.

In what follows, the focus is primarily on the use of satellites to address long-term climate change problems. The important role of satellites for short-term (monthly to seasonal) climate problems is discussed in Chapter 4, which deals with the troposphere.

SCIENTIFIC GOALS

The committee has defined three goals for the study and prediction of long-term climatic changes on the Earth.

The first goal is to observe the long-term (decadal to centennial) trend in global and regional climate as defined by temperature, precipitation, soil moisture, water vapor, and cloud, snow and sea ice cover.

The second goal is to understand (1) the roles of external and internal variations in climate forcing parameters including anthropogenic influences in determining long-term global and regional climate changes; and (2) the physical processes that govern climate sensitivity to variations in climate forcing parameters.

The third goal is to predict the long-term evolution of global and regional climate including the effects of anthropogenic activities, episodic and chronic variations in solar insolation and volcanic activity, and interannual and longer term natural fluctuations in the internal variables of the climate system.

The first goal concerns the determination of the trends in the basic climate variables. Except for temperatures and precipitation over the continents, the long-term trends in the variables that are listed under this goal are largely unknown. Sea surface temperatures over some oceanic regions have been monitored for about a century, but the intercalibration and the spatial scales of the measurements are not sufficient to accurately determine large-scale changes in sea surface temperatures.

Determination of the trends, by themselves, is not sufficient to either develop a quantitative theory of climate change or to establish the anthropogenic influences on climate. As mentioned under the second goal, the relative roles of the various climate forcing terms have to be understood in order to establish the role of anthropogenic influences on the observed climate trend. The physical processes that constitute item (2) of the second goal are those feedback processes that determine the sensitivity of climate to changes in the forcing parameters. Foremost in the development of climate prediction capabilities is improved understanding of the role of the global atmospheric hydrological cycle (evaporation, precipitation, clouds, atmospheric vapor, soil moisture, and groundwater) in the present-day climate as well as in determining climate sensitivity to forcing. The level of present knowledge is such that precipitation over oceans is uncertain by at least a factor of 2. Also the only global cloud cover data set that gives both the vertical distribution of cloud cover and the frequency of occurrence by cloud types (essential for validating climate models) are ship observations collected in the 1930's. It is very difficult, if not impossible, to further our understanding of climate and climate change without making significant progress in our understanding of climate-hydrological cycle feedbacks including the cloud feedback and the snow and ice feedback. Also needed are advances in related areas such as the role of plant canopies in the surface moisture and energy budgets, and the mechanics of air-sea interactions.

The prediction of the long-term evolution of climate can proceed either through global modeling or empirical approaches of estimating the sensitivity of climate to the climate forcing parameters listed in Table 8.1. The list is so large that, in the near term (the next 5 to 10 years) we see significant scientific and practical benefits from improving our physical understanding and ability to predict climate changes in a few selected areas, for example: (1) *Climatic effects of volcanic eruptions*. Ground-based, aircraft, lidar, and satellite measurements have clearly shown that the El Chichon Volcano has had a major impact on the tropospheric radiation budget as well as causing a significant warming of the tropical lower stratosphere. Since the primary radiative effect lasts only a few years, effects on surface and tropospheric climate would depend on the rate of mixing of thermal energy within the upper layers (0 to 50-m depth) of the oceans as well as on stratospheric and tropospheric radiative-dynamical interactions. Furthermore, since a volcanic eruption is an episodic phenomenon, a quantitative understanding of the processes that cause interannual climatic variability, e.g., El Niño, is a prerequisite for assessing the climatic effects of volcanoes from observed climate records. Hence attempts to simulate the climatic effects of volcanic eruptions, in particular those of El Chichon, would be a useful test of climate theories and models. (2) *Effects of desertification and deforestation*. Focused efforts in these two problems would go a long way toward filling the glaring gap in our understanding of the response of climate to regional changes in surface processes. (3) *Effects of minor trace gases*. A study of the climatic effects of minor trace gases is of practical and scientific importance. If the current rate of increase of CO_2, CH_4, $CFCl_3$, and CF_2Cl_2 continues over the next 10 to 20 years, these gases can have a nonnegligible surface warming effect. Hence we should seek to understand the possible atmospheric and climatic effects of the minor trace gases. (4) *Effects of solar radiation changes*. Observations of the solar insolation from space have recently provided solid evidence of fluctuations of the order of 0.1 percent. Such changes occur mainly on a short time scale, but there is also evidence for some longer period trends, associated with the 11-year sunspot cycle. If such low-frequency variations are confirmed as significant, it may have important implications both for interpreting the past climate record and for climate predictions in the future.

SCIENTIFIC OBJECTIVES

Long-term measurements of certain key variables are crucial for improving our knowledge and understanding of climatic changes. *The primary measurement objective for the study and prediction of long-term climatic changes on the Earth is to accomplish each of the following:*

1. *To measure the long-term global and regional trends in external and internal climate forcing terms: the variables that must be measured are solar flux, radiative fluxes at the top of the atmosphere, radiatively important trace gases and aerosols, and certain land surface properties (vegetation cover, soil moisture, albedo, and emissivity).*
2. *To measure the long-term global and regional changes in climate: the variables that must be measured are surface and tropospheric temperatures, precipitation, water vapor, and cloud, snow, and ice cover.*

In addition to these parameters, it is desirable to also measure the following variables: the surface budget of radiative, sensible, and latent heat fluxes; sea level; and cloud liquid water content.

An effective overall strategy requires a research effort balanced between acquiring new research data sets, studying physical processes, and developing global climate models. It is possible that our climate data requirements will continually be modified as we gain deeper understanding of the physical processes and as we develop more complex climate models. The task, then, of designing climate observing systems is a difficult one, particularly in view of the long lead times needed for developing and launching satellite observing systems. For the determination of long-term trends it will be necessary to maintain continuity of measurements for a minimum of a decade to as long as a century. Furthermore, in many instances (e.g., precipitation), the measurement techniques need to be developed to meet the desired accuracy.

A summary of the measurements discussed in the above objectives is provided in Table 8.2. The horizontal scales given in the table are those required for determining the long-term trends and for model studies. The accuracy quoted for the mean refers to the climatological mean, and it is the accuracy required for model verification and for scientific studies. The numbers shown for the accuracy account for all sources of errors: instrumental and sampling. For the mean quantity, the accuracy when it is quoted in percent refers to relative value, i.e., if the albedo is 30 percent then the accuracy is 3 percent (10 percent of 30 percent). The accuracy that is mentioned under the trend column denotes the magnitude of the decadal trend that should be detectable with about 95 percent confidence. The list of variables is so large that the commitment to analysis of the data being collected should likely be as large as the effort to gather the data.

In what follows, the committee will elaborate on the two objectives given above and on the proposed measurements (see Table 8.2) to accomplish these objectives.

Objective 1

Measure the long-term global and regional trends in external and internal climate forcing terms: the variables that must be measured are the solar flux, the radiative fluxes at the top of the atmosphere, radiatively important trace gases and aerosols, and certain land surface properties (vegetation cover, soil moisture, albedo, and emissivity).

As indicated in Table 8.1, most of the external forcing of climate as defined here involves perturbations in radiative heating. One of the fundamental quantities that determines the external forcing is the net radiative heating of the surface-atmosphere system, i.e., the difference between the incoming solar flux absorbed by the surface plus atmosphere and the outgoing longwave flux at the top of the atmosphere. Space platforms provide the best method for measuring this quantity.

Space platforms also provide an ideal method for measuring global

TABLE 8.2. Proposed Measurements for Decadal Climate Trends

	Horizontal Scale[a]	Accuracy	
		Mean	Trend
Climate Forcing Terms			
Top of the atmosphere			
Solar flux	n/a	0.1%	2%
Albedo (spectral and total) (0.3-0.5, 0.5-0.7, 0.7-0.9, 0.9-4 μm)	200 km;	5%	10%[b,d] 5%[c,d]
Longwave flux (spectral and total) (4-7; 7-13; 13-18; 18-100μm)	200 km	5 W/m^2	2 W/m^2 [c,d] 15 W/m^2 [b,d]
Surface			
Latent heat flux	200 km	10 W/m^2	10 W/m^2
Solar and longwave flux	200 km	10 W/m^2	10 W/m^2
Surface albedo	200 km	5%	10%
Vegetation cover (by type)	200 km	10%	10%
Soil moisture	200 km	20%	
Atmosphere, trace gases			
CO_2 column	global mean	5%	5%
Tropospheric ozone column	500 km	10%	5%
Stratospheric ozone column	500 km	10%	10%
Stratospheric water vapor	500 km	15%	15%
CH_4 column	global mean	20%	5%
N_2O column	global mean	20%	5%
$CFCl_3$,CF_2Cl_2 columns	global mean	20%	5%
Others listed in Table 4.1			
Atmosphere, aerosol opacity			
Stratospheric aerosols	500 km	0.01	0.05
Tropospheric aerosols	500 km	0.05	0.05
Atmosphere, clouds			
Total cloud cover	200 km	5%	5%[d]
Cloud type	200 km		
Cloud effective radiating temperatures	200 km	1 K	n/a
Climate Indicators and Hydrologic Cycle			
Surface temperature (land and ocean)	200 km	0.5 K[b] 0.2 K[c]	1 K[b] 0.2 K[c]
Atmospheric temperature			
Troposphere	200 km	1 K[b]	
Stratosphere	500 km	1 K	0.2 K[c]
Precipitation	200 km	10%	10%[c,d]
Water vapor			
Column	200 km	10%	10%[b]
Troposphere (every 2 km)	200 km		5%[c]
Stratosphere (every 2 km up to 25 km)	500 km		20%[b]
Snow cover, albedo	50 km	10%	5%

TABLE 8.2. (continued)

	Horizontal Scale[a]	Accuracy Mean	Trend
Sea ice			
Extent	50 km	10%	5%
Thickness	200 km	1 m	
Cloud liquid water contents[e]	200 km	25%	n/a
Cloud albedos and emissivities[e]	200 km	20%	n/a
Mixed layer depth	200 km	5 m	n/a
Sea level			2-5 cm

[a] Stated scale is the shortest required; scale can be larger for larger scale variations. The scale is also partially determined by the anticipated scale of the next generation (in 1990's) climate models.

[b] Regional.

[c] Global.

[d] The radiation budget, precipitation, and cloud cover have to be measured with a frequency of less than 1 hour with horizontal scales of a few kilometers in order to obtain the desired accuracy. Hence the scales given here should not be confused with the instrumental resolution.

[e] Short-term data set to address feedback processes.

NOTE: For all the variables, except solar insolation and the uniformly mixed trace gases, the annual cycle with 1-month resolution is required. All of the quantities given are also needed for climate monitoring. See pages 133–137 for a further discussion of these measurement requirements.

distributions of radiatively important aerosols and gases and of climatically important surface properties.

MEASUREMENT REQUIREMENTS. Table 8.2 provides a summary of the required resolutions and accuracies, but there are subtleties in these requirements not easily included in tabular form and the *discussions that follow should be regarded as essential footnotes to the table*.

Solar Flux. The establishment of decadal trends in the incident solar radiation at the top of the atmosphere is a measurement of high priority. Both the spectrally integrated (total) values and the spectral distribution should be determined. The accuracy of the annual mean total irradiance should be better than 0.1 percent. The spectral distribution is required to determine possible connections between solar variations and middle atmospheric chemistry, including that of ozone.

Radiative Fluxes at the Top of the Atmosphere. Measurements of the Earth's radiation budget, i.e., solar irradiance, albedo, and outgoing longwave flux, would make fundamental and key contributions to our understanding of long-term climate change provided they satisfy the following requirements: they must include the total energy and its spectral decomposition; estimates should be made for clear-sky and average cloudy conditions; the measurements should be made at least once every 3 hours and for a minimum period of a decade. This last requirement is crucial for avoiding the potentially large sampling errors inherent in earlier experiments. There has been a long history of earth radiation budget measurements. While these measurements have made important contributions to climate dynamics, they possess substantial uncertainties resulting from inadequate spatial and temporal sampling, lack of continuity in the measurements; instrumental calibration drifts, and inadequate accounting of meteorological conditions while converting the intensity measured by the satellite to fluxes needed for climate studies. A NASA satellite experiment, the Earth Radiation Budget Experiment, expected to be operating 1984-1986, avoids some of the pitfalls in the earlier measurements with better spatial and diurnal sampling capabilities. Currently, there are no plans to continue this experiment beyond 1986. In addition, this experiment will measure only spectrally integrated longwave fluxes and albedos.

A number of natural and anthropogenic factors would contribute to long-term changes in albedo. The warming due to CO_2 and other trace gases is estimated to cause a substantial retreat of the sea ice and snow cover, thus resulting in a dramatic decrease in the polar albedo. Clearing of forests and desertification would lead to a substantial increase in the visible albedo. Furthermore, both injection of volcanic aerosols into the stratosphere and decreases in ozone enhance the planetary albedo. Hence albedo measurements are crucial for testing ice albedo feedback theories and for determining the long-term trend in the regional solar forcing of the planet.

The planetary albedo should be determined for the total solar flux as well as for the flux in several discrete broad spectral intervals including the following minimum set: 0.3-0.5 μm, 0.5-0.7 μm, 0.7-0.9 μm, 0.9-4 μm. Furthermore, it is crucial to determine the above albedos for clear-sky conditions as well as for average cloudy conditions. It is from the clear sky values that we can discern changes in the forcing due to changes in surface properties. The measurement of the total spectrum will establish the net change in the solar forcing while the spectral measurements will enable identification of the mechanism. For example, vegetation albedo is significantly (by a factor of 2 to 3) lower in the 0.5- to 0.7-μm region than in the 0.9- to 4-μm region, while the snow albedo is significantly larger in the 0.5- to 0.7-μm region than in the 0.9- to 4-μm region. Changes in ozone will alter the albedos mainly in the 0.3- to 0.5-μm and 0.5- to 0.7-μm region.

The temporal frequency of measurements should take into account the significant high-frequency fluctuations (1 day or so) in albedos due to weather and strong diurnal variations. In order to obtain clear-sky values, the horizontal resolution should be of the order of a few kilometers. The regional albedos should be determined with a relative accuracy of 5 percent (seasonal mean values), and for global and regional albedos, we must be able to detect decadal trends of 5 and 10 percent, respectively.

Similar considerations apply to longwave flux. In addition to the integrated flux, broadband measurements are needed for the following spectral intervals: 4-7 μm; 7-13 μm; 10-13 μm; 13-18 μm. Again, it is important to estimate clear-sky values in addition to measuring average cloud conditions. The 8- to 10-K winter polar surface warming due to doubled CO_2 predicted by models should enhance the total outgoing flux by as much as 20 to 30 W/m^2. The enhancement of the atmospheric greenhouse effect of CO_2 will be manifested in the 13- to 18-μm region. The cloud feedback signature will be concentrated in the 7- to 13-μm interval. Measurement of the 7- to 13-μm interval in conjunction with the 10- to 13-μm interval will help isolate the effects of ozone change (the 9.6-μm band) and volcanic aerosols, provided clear-sky estimates are obtained. The spatial and temporal sampling of the measurements are the same as those mentioned for the albedo.

Radiation budget measurements are also required for establishing regional radiative forcing, the meridional ocean heat transport, indirect estimation of the surface radiation budget, and the role of clouds in the radiative heating of the surface-atmosphere system.

Radiatively Important Trace Gases and Aerosols. Trends in the vertical distribution of the aerosol concentration should be measured in conjunction with measurements of the solar and longwave optical depth within the stratosphere and the troposphere. Monthly mean values over 250 x 250 km regions would be adequate. The committee emphasizes, in particular, the importance of determining the concentrations and optical properties of arctic particulates. High priority should be given to making global measurements of aerosol concentrations and optical depth following major volcanic eruptions. Satellite, ground-based, and aircraft measurements should be used where appropriate to determine the concentrations of the aerosol precursors OCS and SO_2 following volcanic eruptions.

All of the radiatively active minor trace gases in Table 8.1(b) should be measured globally to sufficient accuracy that changes of 2 to 10 percent per decade can be determined. In the case of ozone, special attention should be given to measuring and determining long-term shifts (if any) in the vertical distribution with careful attention given to tropospheric ozone trends.

Land Surface Properties. Satellite and ground-based observations should help determine trends in deforestation, desertification, soil moisture, changing extent of sea ice and snow cover, and the release of heat and moisture from industrial activities. Further discussion of these parameters can be found in Chapter 7 for vegetation, in Chapter 4 for soil moisture, and in Chapter 6 for snow and ice cover.

Objective 2

To measure the long-term global and regional changes in climate: the variables that must be measured are surface and tropospheric temperatures, precipitation, water vapor, and cloud, snow, and ice cover. These measurements, in addition to determining climate trends, are also crucial for determining the role of the feedbacks involving the hydrological cycle, i.e., the interactions between temperatures, water vapor (and its greenhouse effects), precipitation, and clouds.

MEASUREMENT REQUIREMENTS. While a number of these variables are currently being measured by operational satellites, there is a need to improve the accuracy and the frequency of the spatial and temporal sampling. Measurement requirements for each relevant climate parameter are given in Table 8.2. In addition to the variables listed in Table 8.2, for the definition of climate, there is a critical need for a continuous determination of the atmospheric circulation parameters as discussed extensively in Chapter 4.

Surface and tropospheric temperatures. A general discussion of these measurements is provided in Chapter 4. Note in particular that sea surface temperature retrieval techniques are not sophisticated enough to achieve the accuracy mentioned in Table 4.1. The ability to achieve the desired requirement depends critically on discriminating clear-sky regions accurately from regions that are partially covered by clouds; isolating the effects of tropospheric and stratospheric aerosols; and estimating accurately the water vapor distribution.

Precipitation. As mentioned earlier, the present estimates of precipitation and evaporation on a regional basis are uncertain by a factor of 2 or more. We need to establish long-term (decadal) averages and trends for 200 x 200 km regions. The sampling should be sufficient to resolve the strong diurnal and small-scale variations in convective precipitation. The required accuracy for decadal trends is 10 percent for global trends and about 25 percent for regional trends (e.g., shifts in wet and dry zones).

Water Vapor Distribution. This is one of the most important parameters for the theory of long-term climate trends: For example, in model simulations addressing increases in CO_2, the greenhouse effect of the increased H_2O in the warmer troposphere contributes roughly half of the model-computed surface warming. This H_2O

greenhouse amplification is one of the central issues in all climate change problems. Current ground-based operational measurements have unacceptable errors (typically about 25 percent) above 5 km in altitude. In the short term (5 to 10 years) there is a need for accurate (10 percent) measurements, globally, with a vertical resolution of 1 km or better. Such accurate H_2O measurements are also critical for verification of the cloud radiation parameterization in climate models. In the longer term, high priority should be given to estimating global decadal trends of the order of 5 percent.

Clouds. The global distribution of fractional cloud cover, and if possible cloud effective radiating temperatures, albedos, and emissivities, should be measured. The aim here is to determine long-term changes and also the role of clouds in modulating the radiative heating of the system. The International Satellite Cloud Climatology Project (ISCCP) has initiated a 5-year project (1983-1988) to determine the above-cloud properties from polar orbiting and geosynchronous satellite data in order to meet the committee's objectives.

Snow and Ice Cover. Snow and ice cover are indicators of climate change and methods to determine their areal extent are described in Chapter 6. The spatial scale of 50 km given in Table 8.2 is required to determine climatically significant changes in the snow and ice boundaries.

Other Desirable Measurements. The surface radiation budget together with estimates of latent and sensible heat fluxes can be used to infer heat transport within the oceans. While it is difficult to measure the surface radiation budget directly from space, we can explore ways of inferring the surface budget from measurements of the top-of-the-atmosphere radiation budget in conjunction with cloud cover data and detailed radiation models. This procedure has to be validated extensively with ground-based radiation data over carefully selected oceanic and land sites. Also in order to develop and verify coupled ocean-atmosphere models, there is a need to obtain long-term monthly mean estimates of wind stress, surface currents, and the mixed layer depth over the global oceans. (These requirements are discussed in Part I of this report.) Sea level is one of the most valuable indicators of global climate change, but the desired accuracy for decadal trend (Table 8.2, last entry) is extremely difficult to achieve and hence is not heavily emphasized here.

ADVANCES IN THEORY AND MODELING

Global climate models with interactive physical processes in conjunction with observations are valuable tools for testing and developing reliable theories of climate change. Currently, there are models under development that couple the atmosphere, the oceans, and the cryosphere. However, the treatment of several physical processes involving vegetation evapotranspiration, cloud-radiative interactions, air-sea interactions, and the cryosphere needs to be substantially improved before the models can make fundamental contributions to the understanding of the interactive processes as well as serve the role of predicting climate trends. *The committee recommends development of global models incorporating interactions between the atmosphere, land, oceans, ice caps, and biota in order to improve both understanding and accuracy of prediction of regional and global climate*. In order for this recommendation to be implemented, a detailed program including in-situ measurements will be required to better define the physics, dynamics, and thermodynamics of clouds, precipitation, and evapotranspiration and the dynamics of the global oceans and of ocean-atmosphere heat exchanges. (A more extensive discussion of the theory and modeling of climate can be found in *Carbon Dioxide and Climate—A Second Assessment*, National Academy Press, 1982.)

RECORDS OF PAST CLIMATES

The record of past climates contained in sedimentary rocks, sediments, and glacial ice is an invaluable resource for development and testing of complex models of the interactive atmosphere-land-ocean-biota system. The data obtained thus far from rocks, sediments, and ice cores represents only a small sample, however, of the potential record contained in these media over the globe. Expansion of the record will require acquisition and analysis of appropriate samples from these various media with particular attention being applied to ensure that all climate-related aspects of the cores obtained will be investigated: physical structure, isotopic and chemical composition, microfossils, and trapped gases, dust, and organic matter all provide potentially useful information on past climates that should be fully exploited. In addition, as discussed in Chapter 6, remote sensing provides a valuable tool for identifying large-scale patterns indicative of past hydroclimates, which should also be fully exploited.

In addition to the proxy climate data available in the geologic record, direct measurements of climate are available that need to be more extensively studied to provide as accurate a picture as possible of climatic change over the past 100 years. The direct measurements of interest range from the restricted data available on surface climate during the nineteenth century to the extensive record of surface and atmospheric climate contained in existing satellite data and which has not yet been extensively analyzed for this purpose. *The committee recommends that existing satellite data be more fully investigated in order to better define climate and climatic change over the past two decades.*

The committee emphasizes that while models developed in the future may ultimately be successful in simulating the Earth's current climate, this success provides no guarantee that the models contain all of the processes and feedbacks necessary to understand and predict future climatic change. Our knowledge of past climate changes, as incomplete as it may be, provides an important input to model development. *The committee recommends that models for understanding present climate and predicting future climate make maximum use of the data on past climates as a basis for both development and testing.*

9
Science Program Issues

IMPLEMENTATION OF THE STRATEGY

In the preceding chapters of this report, the committee has presented a detailed strategy for the study of the Earth from space. A discussion of how this strategy should be implemented is now appropriate. It is apparent from this strategy that research in the earth sciences requires two types of measurements. On the one hand, long-term measurements embodying evolutionary improvements over earlier instrumentation are being recommended to provide information regarding trends in the atmosphere, land, oceans, and biota. In parallel, the committee wishes to obtain shorter-term measurements of a special character to address pressing scientific issues and to test new instruments. For both types of measurements, *the committee concludes that the present frequency and mix of space flights are not adequate to maintain a vigorous, productive program in the earth sciences*.

Operational satellites, such as those for meteorological and land remote sensing, provide some opportunities for research, but they have been designed primarily to satisfy operational requirements. Because these requirements are nevertheless very important, *the committee recommends that the operational weather satellite system be maintained to include always at least two geostationary and two polar orbiters*. These four orbiters, the committee would emphasize, are minimum requirements for operational purposes but are not sufficient to meet the objectives given in Chapter 4 for tropospheric studies. During a large portion of the Global Weather Experiment of

1979, as many as five geostationary platforms were in orbit. Their contribution to the success of the experiment argues for attempting to achieve this sort of coverage of the global troposphere routinely in the operational system. Of course, beyond simply maintaining the current operational weather systems, it is important to seek improvements in their instrumentation and their data handling components.

In addition to the operational satellites, missions with a research emphasis will be necessary to carry out the strategy outlined in Chapters 3 through 8. These research missions are required not only for short-term measurements of a special character but also for long-term measurements not achieved by operational satellites.

With regard to longer term measurements in general, it is essential to ensure that data records be as homogeneous as possible. Therefore *the committee recommends that intercalibration of instruments to be flown on successive missions that could yield long-term records be an integral part of mission planning*. In many cases, it is also crucial that data records be as continuous as possible. With regard to shorter term measurements of a special nature, the long intervals between launches of research satellites in the earth sciences have discouraged many of the most capable scientists from taking part. The slow pace of these programs does not allow a proper follow-up of earlier developments. As a result, we face the prospect of allowing the lead in many areas of earth science research to pass to other nations who are more dedicated to new technology. It is encouraging to see such programs as the Navy's Remote Ocean Sensing System (NROSS) and NASA's Upper Atmospheric Research Satellite (UARS) being actively pursued, but the approval of these two missions should not lull us into a false sense of security. To ensure the continued development of a vigorous program in the areas of the earth sciences addressed in Chapters 3 through 8, *the committee recommends that at least three research satellites be launched over the next decade, and preferably more*.

As previously mentioned, research satellites for the earth sciences need to include both geostationary and polar orbiters. Observation of different parts of the earth system (e.g., biota, ice and snow, and rocky terrain) using a common multispectral technique and common orbiter would provide maximum efficiency, and the committee suggests that this concept should be developed further. Efficiencies in data collection should also be achieved through the design of innovative approaches for varying the frequency and/or spatial resolution of measurements depending on the target and purpose for the observations.

The effective management of large data bases is a general problem in the space sciences (see *Data Management and Computation, Volume 1: Issues and Recommendations,* National Academy Press, 1982.) In many cases, it is clear that very large amounts of data will be produced by satellites used to study the Earth. Problems associated with data management and analysis in the Earth sciences are addressed in Part I of this report. Because the disciplines covered in Part II of this report deal with extremely large data sets, the committee reemphasizes the importance of this issue. In particular, *the committee recommends that an earth sciences information system be developed through appropriate interagency and international cooperation.* This information system should consider three classes of data and the problems associated with the collection and management of each: data that already exist in archives, data to be acquired from future operational satellites, and data to be gained from future research missions.

The great volume of meteorological and other satellite data already archived has made their access very laborious. It is often difficult for users to discover what satellite data exist let alone be able to utilize them. At the same time, much potentially valuable information may be stored in these data sets. *The committee recommends that the existing satellite data be archived in a form convenient for outside users, and that proper attention be given to documenting, storing, and distributing these reduced data sets.*

The archival problem, of course, confronts the handling of future operational data sets. It is therefore a problem that must be solved. An additional data management issue relates to the current practice at operational meteorological centers where raw radiance information sensed by a satellite is processed into forms that can be easily digested by state-of-the-art analysis schemes (for example, temperature profiles over broad horizontal regions). Later generations of climate researchers may well regret the loss of higher resolution, raw measurements that could have provided a valuable record extending back in time. Therefore *the committee recommends that, in addition to archiving reduced data sets, the information contained in the original radiance observations should also be preserved.*

These issues surrounding data storage must be considered in conjunction with plans for new research satellite missions. Here the interests of not only the principal investigators attached to the mission, but also the wider scientific community, are important. *The committee recommends that data management be addressed as an integral portion of any space mission, and that the views of the interested scientific community be sought in this process.* Moreover, analysis of mission data should also be treated as an individual budget item for several years after the data are acquired. Only in this manner can the desired scientific benefits from a mission be definitely acquired.

MODES OF OBSERVATION FROM SPACE

Implementation of the strategy for the earth sciences developed by the committee carries certain special requirements for space operations that must be satisfied. *The committee is especially concerned about the possibility that NASA may not be able to meet these requirements because the necessary space operations and transportation capabilities will not be available.* Geostationary orbits are required for such observations as continuous measurement on the mesoscale of evaporation, precipitation, and cloud height, thickness, and extent; severe storms; crustal deformation and plate movement; and in-situ measurement relay and integration. In addition, polar or near-polar orbits are needed for observing cryospheric and biospheric inventories; atmospheric inventories; atmospheric temperature, winds, radiation budget, and composition; land surface composition and structure; sea surface elevation, temperature, and wind stress; and the gravity field. Typical altitudes for polar orbiters need to range from 300 to 1000 km. In some cases, circular orbits are required, and for operational meteorology sun-synchronous orbits are required. An orbital emphemeris accuracy of ± 50 m is required for crustal dynamics measurements.

A number of technological and operational needs also exist in order to perform earth science research from space-based platforms. These include flexibility in experimental command, operation, and readout; environmental purity (in particular, freedom from interference from extraneous radiation, electric and magnetic fields, dust, mechanical vibrations, etc.); and a degree of independence of various experimental operations from one another and from central operations facilities (e.g., so that observations of episodic phenomena may be controlled in real time). Pointing directions will vary widely from sub-Earth to anti-Earth points. Required pointing accuracy will range from ± 1 arc sec to ± 1 degree, and a pointing stability of a few arc seconds per minute is demanded by some investigations (particularly for crustal dynamics). Power requirements will range from 0.1 to 10 kW (the largest power demands are for active detectors such as lidars for winds and synthetic aperture radars). Typical instrument payload volumes will range from 1 to 25 m^3, and instrument payload masses from 100 to 2500 kg. Data rates will vary from 1 kbyte/s to 300 Mbyte/s (the largest rates are demanded for synthetic aperture radars and high spatial resolution multispectral imaging).

With the above requirements in mind, it is possible to conceive of utilizing a variety of modes of investigation to accomplish the committee's strategy. Given the difficulties involved in obtaining new program starts, earth sciences research should not rely entirely on major free-fliers for obtaining space-based observations. Although such missions should form the core of the effort, other, less costly means of acquiring measurements from orbit should also be pursued. For example, opportunities to collect long time series of data can be achieved with use of Explorer-type spacecraft. Constraints imposed by these smaller spacecraft will likely spur scientific and technical innovations. While it would not be possible to perform the most comprehensive investigations with such missions, there is the potential for a large return from these more narrowly focused studies. They would also encourage more frequent flights, thereby ensuring greater vitality to the research community. Additional means of acquiring relatively inexpensive data from space include both using the shuttle to test instruments and placing research instruments on future operational satellites. In particular, *the committee recommends that consideration be given to the concept of allocating a constant fraction of the total capacity of operational satellites to payloads addressing long-term measurements for research purposes*.

As an alternative, or a complement, to the free-flier single-mission approach, *the committee recommends that NASA explore the possibility of designing a small, standardized platform that can be used as the basic carrier for a wide variety of earth science and astronomy investigations*. Of course, more than one such platform would be needed to address the diverse needs of the earth sciences. In addition, both low-earth and geostationary orbits are required. Such requirements should be borne in mind with regard to any future plans to use a "space station" to study the Earth.

NONSPACE COMPONENTS

In Part I of this report, the committee made a number of recommendations on issues dealing with the relation of ground and airborne measurements to those taken from space and the need to support relevant theoretical and laboratory studies. The recommendations in these areas still stand; indeed, the committee would emphasize again the vital importance of sustaining a coordinated program of space-based and ground-truth measurements. This point has been recognized, for example, in the design of the International Satellite Land-Surface

Climatology Project (ISLSCP) supported by the United Nations Environment Program. The planning for ISLSCP includes an initial program of making satellite measurements at the same time as those taken at the surface to calibrate, validate, and interpret the satellite-viewed radiances in terms of the physical properties of the ground. Moreover, a series of ground sites will be maintained throughout the duration of ISLSCP to validate the satellite observations repeatedly in space and time. This approach could perhaps serve as a model for future satellite programs.

AGENCY INTERACTIONS

The interdisciplinary nature of many of the research objectives described in this report poses a challenge to scientists and administrators alike. It was considered an important policy issue in Part I of this strategy. Traditionally, science has proceeded within well-defined disciplinary boundaries. However, many of the problems now faced require expertise across a broad spectrum of the physical and biological sciences. The research community has become aware of this need, but more should be done within NASA and other agencies to facilitate and encourage the funding of worthwhile interdisciplinary research. There is currently too great a chance for such proposals to "fall through the cracks" between individual program boundaries. As a step toward ameliorating the problem, *the committee recommends that the earth science and global biological science programs within NASA be integrated into a single section with common long-range planning and goals*.

Problems also arise as a result of the fundamentally different perspectives under which the two mission agencies that utilize satellites, i.e., NASA and NOAA, operate. The mission of NASA has primarily been that of experimentation and development. Once a space system has been proven, it generally falls under NOAA's domain for operation. NOAA, faced with severe budgetary constraints over recent years, has often been unable to provide sufficient funding for the research necessary to use space-based data adequately or to ensure the integrity of the data sets required to study long-term trends. This is of serious concern to members of the scientific community who look to the operational data sets for much of their research.

Tragically, much important information that is needed to address the scientific goals outlined earlier is being lost to the exigencies of operational requirements that must be met within tight budgets. Thus, for example, little attention is paid to the inhomogeneities that are introduced into meteorological time series by routine or more major changes in procedures at the National Meterological Center. Such inhomogeneities can play havoc with attempts to establish the true range of climatic variations. This example points to the priority that must be placed on increasing the research efforts within NOAA or through its funding of extramural research.

Other agencies also have interests in space-based data. NSF supports theoretical, laboratory, and ground-based observational studies that are directly relevant to NASA's and NOAA's programs. In addition, DOE, USDA, and DOD all have ongoing programs related to space. Cooperative endeavors among these agencies should be pursued wherever possible.

In a related matter, the committee is aware of proposals that the operational meteorological and land resource satellite systems be transferred to commercial interests. While it is beyond this committee's purview to affect these plans directly, the committee nevertheless feels compelled to express its view that provisions must be made for satellite data to be properly managed. The concerns the committee has expressed about satellite data management within NOAA's operational centers and elsewhere naturally extend to any other organization that may end up with control of these data. Given the recognition that commercial interests are not often driven by a desire to maintain long-term, high-quality data for scientific research, these proposals are of particular concern. *The committee recommends that, should commercialization of the meteorological and land resource satellite systems now in NOAA proceed, the commercially operated system must include means to assure access to the satellite data by the scientific community on a timely and inexpensive basis.*

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Science Policy Considerations

Part I of this report raised several important policy issues and concerns that were an implicit part of the formulation and planned implementation of this strategy. Two years have passed since the release of Part I, and, generally, these issues still remain. As Part II of this report completes the strategy for earth science from space, it is both timely and appropriate to repeat some discussion of those outstanding concerns.

GLOBAL PERSPECTIVE

The fundamental conclusion upon which both parts of this strategy is based is that earth exploration from space must be global in scope. Further, in order to realize the fullest potential of this strategy, it is imperative that a commitment be made to maintain a vigorous and sustained systematic program of earth exploration from space.

NATIONAL SPACE POLICY

One of the basic issues that must be addressed in implementing this earth sciences strategy is the broad question of a unified national space policy. It is widely recognized in the scientific community, industry, and government that a unified civilian space policy does not exist. Rather, it has been left to the President and Congress to make year-to-year decisions regarding space projects and programs. These decisions are made, necessarily, in the context of fiscal and political considerations that, in the long term, may not provide the greatest value to this country's present and future space efforts. The committee reiterates the observation made in Part I of this report that for the earth sciences ". . . the lack of a national policy for space exploration is a major obstacle to achieving the present strategy."

INTERNATIONAL ACTIVITIES

It was noted in Part I, and it is still understood, that there has been considerable interest and planning by other countries with respect to studying the Earth from a global perspective. In fact, over two dozen national and international programs currently exist or are being planned that aim to increase man's understanding of some portion of the Earth and its environment. For example, the committee is aware of NASA's plans for a Global Habitability Program, which could potentially aid in the nurturing of interdisciplinary research concerning changes in the habitable Earth on time scales of 5 to 100 years. All of these efforts recognize the global-scale nature of this endeavor and therefore look to satellite measurements as a central part of their design. Proposals have been made to coordinate these separate programs so that their scope is broadened to embrace all the physical, biological, and ecological processes important to the habitability of the globe. For example, the International Geosphere-Biosphere-Program (IGBP) (see *Toward an International Geosphere-Biosphere Program—A Study of Global Change*, National Academy Press, 1983) would focus on the central theme of global change and would encompass at least a decade of research. The *committee recommends that NASA establish and maintain a liaison with such programs to aid in the coordination of its research plans with those of the international community*.

EARTH SCIENCES JURISDICTION

As the domestic and international interest in space-based earth sciences research has grown, so too has the awareness of the rather ad hoc division among various federal agencies of the responsibility for these efforts. In Chapter 9, some of the practical programmatic effects of this division are discussed. While it is beyond the purview of this committee to make recommendations on specific institutional arrangements in this regard, the committee believes that it is imperative that the overall issue of jurisdiction for earth sciences programs and research be resolved.

The committee reemphasizes the observation made in Part I that given the high level of importance assigned to the science strategy and the policy implications of its subsequent applications, an optimal organization for global program responsibility is vital and deserves primary consideration.