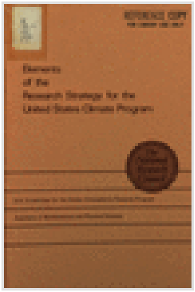

Elements of the Research Strategy for the United States Climate Program (1978)

Pages
54

Size
5 x 8

ISBN
030933506X

Climate Dynamics Panel; U.S. Committee for the Global Atmospheric Research Program; Assembly of Mathematical and Physical Sciences; National Research Council

Elements of the Research Strategy for the United States Climate Program

Report of the
Climate Dynamics Panel
to the
U.S. Committee for the
Global Atmospheric Research Program
Assembly of Mathematical and Physical Sciences
National Research Council

NATIONAL ACADEMY OF SCIENCES Washington, D.C. 1978

The activities of the United States Committee for the Global Atmospheric Research Program leading to this report have been supported by the National Oceanic and Atmospheric Administration and the National Science Foundation under Contract NSF-C310, Task Order No. 197.

Available from
U.S. Committee for the Global Atmospheric Research Program
2101 Constitution Avenue
Washington, D.C. 20418

U.S. Committee for the
Global Atmospheric Research Program

Verner E. Suomi, University of Wisconsin, *Chairman*
Francis P. Bretherton, National Center for Atmospheric Research, *Vice Chairman*
D. James Baker, Jr., Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration
John Imbrie, Brown University
Tiruvalam N. Krishnamurti, Florida State University
John E. Kutzbach, University of Wisconsin
Richard S. Lindzen, Harvard University
Syukuro Manabe, Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration
Norman A. Phillips, National Meteorological Center, National Oceanic and Atmospheric Administration
Richard J. Reed, University of Washington
Henry M. Stommel, Massachusetts Institute of Technology
Carl I. Wunsch, Massachusetts Institute of Technology

John S. Perry, National Research Council, *Executive Scientist*
Thomas H. R. O'Neill, National Research Council, *Consultant*
John R. Sievers, National Research Council, *Executive Secretary*

Liaison with Federal Agencies

Eugene W. Bierly, National Science Foundation
Kenneth W. Ruggles, Department of Defense
Douglas H. Sargeant, National Oceanic and Atmospheric Administration
Pitt Thome, National Aeronautics and Space Administration

Climate Dynamics Panel

John E. Kutzbach, University of Wisconsin, *Chairman*
Allan R. Robinson, Harvard University, *Vice Chairman*
D. James Baker, Jr., Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration
W. Lawrence Gates, Oregon State University
William R. Holland, National Center for Atmospheric Research
Syukuro Manabe, Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration
Stephen H. Schneider, National Center for Atmospheric Research
Norbert Untersteiner, University of Washington
Thomas H. Vonder Haar, Colorado State University
John M. Wallace, University of Washington

Foreword

Over the past few years many factors have been at work to emphasize the importance of climate to man: the drought in the Sahel, the severe winters of 1977 and 1978, and the growing energy-environment enigma to mention a few. These are the "what" and "why" questions of climate. Mounting interest in providing answers to these questions has created a more favorable "climate" for new efforts in climate research. An equally important question is the "how" of tackling the problem. Thus, this report of the Climate Dynamics Panel, U.S. Committee for the Global Atmospheric Research Program, is especially timely because it sets forth some very useful guidelines on a research strategy for a United States climate program.

This report emphasizes a better understanding of the annual cycle *as a first step* in a continuing comprehensive program (see Recommendation 4). Clearly, if we do not understand in a quantitative manner the large changes in our annual climate, how should we be able to usefully understand the more subtle changes that occur from year to year and from place to place?

Here again, the timing of the report is fortunate because the nations of the world are about to carry out an unprecedented effort to observe the global atmosphere well enough so it can be considered a complete physical system. The data provided by the First GARP Global Experiment (FGGE) to be conducted during 1978–1979 should provide the most complete data set ever on which to start a comprehensive research program on the annual cycle. FGGE's first purpose is to better understand the general atmospheric circulation that controls both the global weather and climate. The research strategy advocated in this document and the forthcoming global observations set the stage for a significant advance in our understanding of climate mechanisms.

On behalf of the U.S. Committee for the Global Atmospheric Research Program, I wish to express our deep appreciation to the Climate Dynamics Panel and especially to its Chairman, John E. Kutzbach, for this highly useful report.

Verner E. Suomi, *Chairman*
U.S. Committee for the
Global Atmospheric Research Program

Preface

This report focuses on the short term (1978–1983) research strategy for a portion of the United States climate program. It is intended to supplement material presented in an earlier report, *Understanding Climatic Change: A Program for Action* (U.S. Committee for the Global Atmospheric Research Program, 1975), which laid a broad foundation for the national climate research program. In addition to this document, other publications were used as source material for this report (see Bibliography). Because many details of the research strategy for a United States climate program remain to be determined, the title emphasizes "elements" of the research strategy. This report focuses on the physical-chemical aspects of the climate system. For example, the report omits discussion of two important aspects of a truly comprehensive climate research program:

1. *Climate Information Services*. That is, the task of making up-to-date climate information available to users.
2. *Climate-Change Impact Studies*. That is, the task of estimating cost–benefit ratios associated with climate-change scenarios in such areas as agriculture, energy, water resources, and transportation.

The omission of these elements is not intended to detract from their importance. Rather, it is an attempt to narrow the focus. There are important links between the research program described here and the development of climate information services and climate impact studies. For example, certain data sets needed for climate research will also provide climate information for users, and the climate-change impact studies will help to identify situations and time scales for which specific climate information would be most useful.

1 Objectives and Principal Recommendations

1.1 OBJECTIVES

The objectives of the climate research program described in this report are as follows:

1. To obtain a better understanding of the processes that govern the present climate and to determine the nature and extent of natural climate variability (climate diagnosis). Such information will be of great importance in the pursuit of the following two objectives.
2. To assess the degree to which climate is sensitive to mankind's activities and, to the extent it proves possible, to develop a capability for such sensitivity assessment (climate sensitivity).
3. To assess the degree to which climate is predictable on time scales of seasons to decades and, to the extent it proves possible, to develop a capability for such prediction (climate predictability).

Climate diagnosis involves identifying and understanding the nature of the physical climate processes, including interactions between different components of the climate system (atmosphere, ocean, cryosphere, land surface, biosphere).

A *climate sensitivity* study involves evaluating how a climate in equilibrium is altered under the influence of some "forcing" mechanism such as an increased atmospheric CO_2 content—in other words, to determine and compare two equilibrium states of the climate (assuming that stable equilibrium states exist) with and without some modification.

A *climate predictability* study involves evaluating the time-dependent evolution of the climate—given the present climate, what will the climate be like one month, one season, one year, or a decade from now?

Fulfillment of objectives 2 and 3 will depend to a certain extent on progress toward objective 1. However, knowledge of *how* the climate system operates can be very useful in sensitivity and predictability studies and need not require a *complete* understanding of the system. Thus, research in these three areas can proceed in parallel.

The research strategy for the climate program builds from a base of considerable knowledge, summarized briefly in Chapter 2. The degree to which climate is predictable is not yet known, nor can the degree to which climate is sensitive to man-made changes be assessed. However, there is sufficient information to define the elements of an expanded research program that will address these questions.

Two lines of research activities are anticipated: (1) efforts of individual scientists covering a range of theoretical and empirical studies and, concurrently, (2) joint efforts of many scientists concentrating on the following four major tasks:

1. Development and maintenance of an accessible data base.
2. Development and maintenance of an observing/monitoring system.
3. Development and conduct of climate process experiments.
4. Development of climate models.

Chapter 3 provides a long-term strategy for these four major activities. Chapter 4 provides a detailed listing of major activities to be continued or initiated during the five-year period from 1978 to 1983. It concludes with a discussion of how these activities should contribute to the program objectives in climate diagnosis, climate sensitivity, and climate predictability.

1.2 PRINCIPAL RECOMMENDATIONS

The principal recommendations are as follows:

1. *It is recommended that the instrumental record climate data base be properly assembled, checked, synthesized, and made easily accessible to scientists engaged in climate research* (see Sections 3.2.1 and 4.1). Many of the data sets needed for climate research will also provide information for users. Therefore, efforts invested in this area should yield immediate and long-term benefits.

2. *It is recommended that the noninstrumental record climate data base be further developed* (see Sections 3.2.1 and 4.1). The instrumental record is relatively short and geographically incomplete. Heavy reliance must be placed on the analysis of noninstrumental records to determine patterns and processes of natural climate variation at time scales longer than a decade.

3. *It is recommended that opportunities for application of current technology to more efficient acquisition, processing, and retrieval of climate data be exploited* (see Sections 3.2.1 and 4.1). Climate data sets contain information on a large number of variables collected from the entire globe and a large data volume, particularly for observations from spacecraft. The needed climate data set is far larger than that now routinely processed for weather analysis and prediction. An investment in both scientific manpower and technology is required to deal with the management of future as well as present data sets. As noted in Recommendation 1, some of these data sets will have immediate user applications as well as research applications.

4. *The present and near-future global observing system is best suited for detailed studies of the annual (seasonal) cycle of the atmosphere and its lower boundary (land surface, ice surface, ocean surface). Because these studies are scientifically important for a basic understanding of climate, it is recommended that they receive high priority initially. Because the First GARP Global Experiment (FGGE) offers the opportunity for the detailed study of one seasonal cycle on a global basis, it is recommended that support of FGGE, FGGE subprograms, and post-FGGE data analysis be given high priority* (see Sections 3.2.2, 3.2.3, 4.2, and 4.3). The annual cycle of solar radiation forcing produces large annual responses in the climate system. The variation of seasonal climate in a single year is of the same magnitude as the variation in mean climate over the course of a glacial–interglacial cycle. A better knowledge and understanding of the large response to large, accurately known changes in forcing should provide a basis for the study of smaller interannual and long-term variations due to smaller natural or man-made changes. A more complete knowledge of the interhemispheric climate differences will indicate the influence of continentality on climate response.

The "present and near-future global observing system" refers to World Weather Watch (WWW) observations plus operational and research satellite observations already planned for the First GARP Global Experiment (FGGE) and post-FGGE periods. While this observing system is best suited to the study of the annual cycle of the atmosphere and its lower boundary, certain variables will *not* be adequately observed (for example, precipitation), and special efforts will be required to fill these gaps as they are identified.

The annual cycle of the atmosphere is moderated by the ocean with its large capacity for heat storage. New observational systems should be developed to define the annual cycle in the oceans and to study the interaction between the ocean and the atmosphere.

5. *The present and near-future global observing system is suitable for exploratory studies of interannual variation of the atmosphere and its lower boundary. Because these studies will help to determine the feasibility of short-term climate prediction, it is recommended that they also receive high priority*

initially. It is recommended that the initial climate observing system of the 1980's (post-FGGE) provide for a continuation of the measurements from the operational and experimental satellite and WWW portions of the FGGE observing system, along with continued provisions for data processing (see Sections 3.2.2 and 4.2). The study of short-term climate predictability can be separated into two phases. The first phase would determine whether the atmosphere responds to changes in some measurable variable, especially lower-boundary variables such as ocean-surface temperature. If it does, the second phase would try to predict the variable or variables. The present and near-future global observing system (defined above) is suitable for the first of these two phases, although certain gaps may exist, for example, insufficiently accurate estimates of soil moisture, sea-ice extent and concentration, and solar irradiance. It will be important to try to fill these gaps and to develop an improved observing system that would permit the second phase.

6. *To support the evolving climate observing system, it is recommended that there be a continuous program to develop and test new concepts, instruments, systems, and observing strategies* (see Sections 3.2.2 and 4.2). The next ten years should be a test period for the development and optimization of a composite global climate observing and monitoring system for the late 1980's. Such a test program will also provide crucial data for filling gaps in the present observing system and provide some continuity for observations now available from experimental systems.

7. *It is recommended that the experimental monitoring system should consist of a subset of the current observing system measurements, along with a limited number of additional measurements including experimental ocean monitoring* (see Sections 3.2.2 and 4.2).

8. *It is recommended that selected process experiments in the atmosphere, land surface, ocean, and cryosphere receive high priority initially* (see Sections 3.2.3 and 4.3). These experiments should lead to improvements in the design of the global observing system by the mid to late 1980's.

9. *It is recommended that the development and validation of coupled climate models of various design be a high-priority task* (see Sections 3.2.4 and 4.4). Coupled climate models incorporate processes and couplings of the atmosphere, ocean, cryosphere, and land surface. They provide a measure of our knowledge and understanding and are essential for predictability and sensitivity studies. Modeling studies, together with observational studies, will aid in the specification and simulation of future observing systems and system components.

10. *Skilled manpower in most of the disciplines needed for climate research appears adequate for the initial tasks. However, it is not clear that this talent will be effectively organized. It is recommended that the government plan for means of facilitating involvement of the entire climate research community in the U.S. climate program* (see Section 4.6.1). Some guidelines are as follows:

(a) Arrangements for longer-term research support, since specific climate research problems may require considerable time to define and to attack;

(b) Arrangements for extensive scientist exchange between government agency and university climate research activities; and

(c) Arrangements for increasing the effectiveness of university research programs via grant support that would permit increases in scientific staff and effective access to data banks and large computers.

11. *Climate is a global phenomenon with global impacts, and the study of climate requires global observations. Therefore, active participation of many nations in the World Climate Program of the World Meteorological Organization (WMO) is a basic requirement for progress and should be actively pursued. It is, therefore, recommended that, for greatest effectiveness, the U.S. climate research program be fully coordinated and integrated with the international program.*

12. *At the national level, the program is of such magnitude that it requires the efforts of all agencies with relevant expertise and resources. It is, therefore, recommended that the climate research program be coordinated at a sufficiently high government level to ensure that all agencies contribute appropriately.*

2
Status of Present Knowledge

The status of present knowledge in the areas of climate diagnosis, sensitivity studies, and predictability studies is summarized below.

2.1 CLIMATE DIAGNOSIS

2.1.1. Mean Annual Climate, Mean Seasonal Climate, and Mean Annual Variation

The general atmospheric circulation has been studied intensively for over 20 years. A substantial base of information on atmospheric thermal structure, flow patterns, and mass, momentum, and energy budgets now exists. Most observational studies, however, are limited to the region poleward of 20° N in the northern hemisphere, which has the best radiosonde coverage. Considerable work remains to be done in the study of tropical and southern hemisphere circulations and their incorporation into global general circulation studies. Our conceptual understanding of the general midlatitude circulation is limited. There are important differences in the circulation and climate of the northern and southern hemispheres. These differences must be due to the locations, shapes, and sizes of the continents, but they are not yet quantitatively understood and, at this stage, cannot be said to have been predictable. Further understanding of the general circulation will require integration of regional, conventional surface, and radiosonde observing systems, with satellite-based global observing systems. This work has just begun.

The ocean, land surface, and overlying atmosphere go through a pronounced seasonal cycle in most regions of the globe in response to annual variations in the latitudinal distribution of incoming solar radiation. This mean seasonal cycle has been documented in many locations and for many climate variables. However, scientists are far from a detailed understanding of why the seasonal cycle takes the form it does. For example, the seasonal snow cover produces a large annual variation of the surface albedo, but the role of this snow cover in determining the global heat balance and in forcing the large-scale circulation patterns is not fully understood.

Because of observational difficulties, much remains unknown about the atmospheric moisture budget and the distribution in space and time of the diabatic heat sources—radiation and sensible and latent heating. Estimates of precipitation over the oceans and certain land areas vary widely, so that uncertainties of ±50 percent apply in some regions. Many fundamental questions of atmospheric dynamics and thermodynamics are not understood sufficiently to incorporate these processes, either explicitly or implicitly, in climate models, for example, mesoscale and cyclone-scale interactions or cyclone- and planetary-wave-scale interactions.

Because of observational difficulties, ocean general circulation studies are in a much earlier stage of development than atmospheric studies. The nature of important ocean processes that must be included in any general coupled atmosphere–ocean model, such as upper-layer dynamics, atmospheric interaction, mesoscale eddies, western boundary currents, and water mass formation, are only now being addressed. Some features of the ocean circulation can be deduced from planetary budget studies. For example, it is now possible to estimate the relative roles of the atmosphere and the ocean in poleward heat transport through earth radiation budget measurements obtained from satellites, atmospheric heat transport calculations, and estimates of heat storage in the upper ocean. These estimates indicate that poleward heat transport is of the same order of magnitude in the atmosphere and the ocean. This underlines the importance of viewing the climate system as a coupled atmosphere–ocean system. The annual cycle of the ocean is not well known, except for surface temperature and currents. However, large changes of seasonal heat storage in the upper ocean moderate the seasonal atmospheric cycle, and seasonal variations occur in meridional heat transport by ocean currents. The seasonal reversal of surface currents in parts of the Indian Ocean is a particularly dramatic example of seasonal (monsoon) atmosphere–ocean coupling.

Sea ice in polar oceans undergoes significant seasonal changes in extent, concentration, thickness, and surface characteristics. Process studies are helping to document and understand these changes.

Modeling or simulating the observed behavior is one measure of our understanding of the atmosphere, ocean, or climate. Simulation of the general atmospheric circulation is relatively advanced. Many of the large-scale circulation features have been successfully simulated, including some but not all of the differences between the circulations of the two hemispheres. However, certain climate variables, such as ocean-surface temperature and sea ice, are often treated as boundary conditions in these models. Simulation of the annual cycle of the atmospheric circulation has also been achieved, although without fully coupled climate models. Ocean general circulation models have been constructed, but, without an adequate oceanic data base, comparing simulation to observations is difficult. *Development and validation of fully coupled models—atmosphere, ocean, sea ice, and land surface—are among the major tasks for future climate research.*

In summary, a fundamental understanding of the present climate—mean annual, mean seasonal, and mean annual variation—is far from being realized, but a considerable knowledge base is available.

The proposed climate research strategy will address questions of climate at the same time that it addresses questions of climate variation.

The present status of climate diagnosis of the annual cycle in terms of the four major activities identified in Chapter 1 can be summarized as follows:

Data Base. The existing data base, although useful for many exploratory studies, is inadequate for detailed diagnostic studies because of the lack of atmospheric observations over the ocean, the lack of observations of certain variables related to the diabatic heating of the atmosphere (heating associated with condensation), and the lack of observations of the oceans and sea ice. Certain data sets are also not easily accessible.

Observing Systems. The present atmospheric observing system is inadequate over the oceans and sea ice and for variables related to diabatic heating. Except for ocean-surface temperature, a global ocean observing system does not exist. The FGGE observing system will represent an important improvement for atmospheric observations.

Process/Regional Studies. FGGE and its various subprograms, such as the Monsoon Experiment (MONEX) and the Polar Experiment (POLEX), should provide data sets that will be useful for the study of *one* seasonal cycle. The GARP Atlantic Tropical Experiment (GATE) data, now being analyzed, should fill important gaps in our knowledge of atmospheric circulation over the tropical oceans. Various ocean and sea-ice process experiments in the analysis or field stage, such as the Indian Ocean Experiment (INDEX), the International Southern Ocean Studies (ISOS), and the North Pacific Experiment (NORPAX), should help to define basic processes.

Climate Models. Atmospheric general circulation models are well advanced; however, model intercomparisons and improvements are needed. Ocean general circulation models are in the early stages of development. Development of coupled atmosphere-ocean circulation models has begun but remains largely a future task.

2.1.2 Monthly or Seasonal Departures from the Mean Annual Climate (Interannual Variations)

Considerable monthly or seasonal climate anomalies from its mean annual variation have been observed. The winter of 1976–1977 provides the most recent example. In addition to the year-to-year changes in atmosphere circulation, temperature, and precipitation patterns, considerable year-to-year variations occur in the ocean-surface temperature and circulation patterns and the extent of sea ice and of continental snow cover. Diagnostic studies of these short-term climate anomalies are in progress in the form of statistical studies that infer the statistical structure of the anomalies based on many years of data and case studies that estimate the detailed evolution of a particular anomaly. A number of hypotheses to explain the observed variability have been posed, but none of these can yet be said to be proven. The potential sources of the observed variability could include atmospheric dynamics, atmosphere–ocean–cryosphere–land surface couplings or feedbacks, and external processes such as volcanic eruptions, solar variability, or tidal effects. Combinations of these internal and external processes may be involved.

The existence of a substantial although inadequate data base and the collective experience of long-range forecast groups have produced empirical estimates of predictability at these time scales (see Section 2.3). General circulation models are being used to study the sensitivity of the simulated atmospheric circulation to changes in the ocean-surface temperature or other boundary conditions (see Section 2.2).

The present status of climate diagnosis of interannual variations in terms of the four major activities identified in Chapter 1 can be summarized as follows:

Data Base. For statistical studies it is important to have *long* records of all available data. For case studies it is important that the data sets be complete enough to permit estimation of changes from the average in such categories as energy, moisture, and momentum budgets. The data sets need not necessarily be long. For both categories of diagnostic studies, a data base already exists, but current research is difficult because the data sets are neither easily accessible nor sufficiently complete.

Observing System. The same points apply here as in the annual variation studies, with the additional requirement that the observing systems must be operated for a number of years (see Section 3.2.2) to obtain a data base for the detailed study of short-term climate variations.

Process/Regional Studies. Based on hypotheses derived primarily from recent diagnostic studies, process/regional experiments focused on problems of interannual variations are being defined. Examples include the study of year-to-year variations in midlatitude upper-ocean heat storage or year-to-year variations in equatorial ocean currents and temperature.

Climate Models. The same points apply here as in the annual variation studies. Sensitivity experiments on existing models, coupled with observational studies, help to identify possible interactions between the various components of the climate system.

2.1.3 Long-Term Variations

The causes of long-term climate variation are not known; both external and internal processes have been identified as possible candidates. These processes include, but are not limited to, those mentioned in connection with short-term variations.

Observational studies of long-term atmosphere–ocean variations are based on long isolated instrumental records (100 to 200 years in certain locations) and noninstrumental records that span the entire several-billion-year history of the earth. The most detailed studies of the recent past (the past thousand years) are based on tree-ring records and on early historical records. Land pollen and ocean sediment records are helping to define the climate characteristics of earlier periods. Glacial climates are receiving intensive study, especially the full glacial conditions of 18,000 years before present under the Climate: Long-Range Investigation, Mapping and Prediction (CLIMAP) project. Some recent studies tend to support the long-standing hypothesis that variations in orbital parameters of the earth may play a significant role in producing glacial–interglacial fluctuations.

These studies of long-term climate variations using noninstrumental records are beginning to provide detailed information on time and space scales and, in some cases, processes of climate at time scales too long to be resolved by the short instrumental record, i.e., decades, centuries, and millenia. In certain circumstances, knowledge of climate response over long time scales can also provide useful information about short-term climate sensitivity. Finally, a knowledge of past climates provides a data base for model validation purposes, e.g., the ability of a climate model to simulate a past climatic state or past climate change provides a measure of model reliability.

The present status of climate diagnosis of long-term variations in terms of the four major activities identified in Chapter 1 can be summarized as follows:

Data Base. Historical records, tree-ring records, pollen records from lake and bog sediments, and planktonic records from ocean sediments are already providing useful information concerning past climates. With one or two noteworthy exceptions—the establishment of an International Tree-Ring Data Bank and the 18,000 years-before-present CLIMAP data bank—these data sets have not been assembled for purposes of global climate studies. This needs to be done.

Observing System. The observing system in this context has the unique capability of looking to the past. The tools include ships, planes, and land vehicles to reach observing sites and laboratory facilities for dating and isotope analysis. Because the past climate has not left a continuous and worldwide record, it will never be possible to obtain complete global analyses of all climate states. However, the records are adequate for the study of regional or near-global climate variations during specified time intervals.

Process/Regional Studies. The nature of these studies can be illustrated by some examples. The CLIMAP group has used fossil records from ocean sediments to investigate the timing of upper-ocean and deep-ocean events through a glacial cycle. Others have used pollen records from lake and bog sediments to investigate movements in vegetation boundaries over the past 10,000 years, e.g., the Climate of the Holocene Mapping with Pollen group (COHMAP). Combinations of data on vegetation, extent of land ice, lake levels, and ocean state will permit studies of the timing relationships between the ocean, the ice sheets, and the atmosphere.

Climate Models. Fully coupled climate models—atmosphere, ocean, cryosphere, biosphere, and land surface—are required to simulate past climates and past climate changes and to test our knowledge of long-term climate variations. Such models are not yet available.

2.2 SENSITIVITY STUDIES

Atmospheric general circulation models and simplified climate models are being used to give estimates of atmospheric or climate response to specified changes in some part of the climate system. These studies are a first step toward estimating the regional climate response of the coupled climate system to prescribed changes such as the CO_2 level. The following examples illustrate the current state of this work:

1. Atmospheric general circulation models and simplified atmosphere-ocean coupled models have been used to simulate the climate response to seasonal changes in the distribution of incoming solar radiation. Model simulations capture certain basic features of the observed seasonal cycle.

2. Atmospheric general circulation models have been used to simulate the atmospheric response to changes in tropical or midlatitude ocean-surface temperature. In some cases, the model response is similar to results suggested by observational studies.

3. Atmospheric general circulation models have been used to simulate the atmospheric response to variations in the CO_2 content, solar irradiance, cloudiness, and land-surface modification (albedo, soil moisture). The simulations have

been useful for preliminary estimates of the sensitivity of the atmospheric response to these parameter variations.

4. Observations suggest a relation between volcanic eruptions and surface temperature. Simplified climate models have been used to simulate such a climate response.

5. There is observational evidence that major changes in climate over the past 500,000 years have been related to secular variations in the earth's orbit. Climate response to variations in orbital parameters in simplified climate models agree reasonably well with the observational evidence.

6. Models of various complexity have simulated planetary climates (Mars, Venus) with different external parameters—distance from the sun, size, rotation rate, and atmospheric composition. Space probes also provide observational data on planetary climates.

7. Laboratory experiments with rotating fluids (annulus or dishpan experiments) are capable of generating climates that can be altered by variations in rotation rate, container configuration, and heating, for example.

The present status of climate sensitivity studies in terms of the four major activities identified in Chapter 1 can be summarized as follows:

Data Bank. Data sets are required for model development and model validation. The deficiencies in climate data sets noted in Section 2.1 are delaying certain aspects of this work.

Observing System. Data sets more comprehensive and accurate than those currently available will be required for continued model development and model validation. Improvements in the observing system are required.

Process/Regional Studies. Process studies of the CO_2, the ozone, and the aerosol cycles are needed to improve our understanding of these processes so they can be included in climate models. Some of these studies are already in progress; others are being planned.

Climate Models. Fully coupled climate models, including such variables as CO_2 and ozone, are the ultimate tool for sensitivity studies. Such models are not yet available.

2.3 PREDICTABILITY STUDIES

Theoretical work on climate predictability is just beginning. Theoretical studies indicate that a fundamental uncertainty is imposed on the predictability of monthly and seasonal climate averages because such relatively short time averages are inadequate for filtering out the detailed weather fluctuations that are assumed to be unpredictable beyond several days. This constraint seems to be particularly severe in midlatitudes where day-to-day weather variability is large. Thus, the information contained in a prediction will be statistical—averages and measures of variability, for example—and expressed in terms of probabilities. The prediction of individual events of a particular month or season is an unlikely possibility. Some relevant empirical studies are as follows:

1. The experience of long-range forecast groups in midlatitudes, gained over many years, is that small but detectable predictive skill exists for monthly and seasonal forecasts. In general, this positive skill is greater for temperature forecasts than for precipitation forecasts. Long-range forecasts are probability statements. For example, if temperatures are divided into three equally probable categories of below average, average, and above average based on long-term statistics, a hypothetical monthly or seasonal forecast might state that a particular region may expect above average temperatures with a probability of about one half, average temperatures with a probability of about one third, and below average temperatures with a probability of about one sixth. That is, the forecasts involve a shift in the "odds" from those expected from a random forecast (one third in each category for this example).
2. Evidence exists that at some time scales various geographic regions may have different degrees of predictability.
3. There is evidence that at certain times the short-term climate evolution can be estimated from a knowledge of an existing climate state (precursors to El Niño, for example).

The present status of climate predictability studies in terms of the four major activities identified in Chapter 1 can be summarized as follows:

Data Bank. The same basic status as for climate diagnosis exists here. Data sets are required for model development and model validation. The deficiencies in climate data sets noted in Section 2.1 are, therefore, delaying certain aspects of this work.

Observing System. More accurate and comprehensive data sets are required for model development and for assessment of results of predictability experiments. Therefore, improvements in the observing system are required.

Process/Regional Studies. Process/regional studies are required for model development, and their status is discussed in Sections 2.1.1 and 2.1.2.

Climate Models. Climate models that incorporate certain time-dependent features of the lower boundary (ocean temperature and snow cover, for example) are needed, and development work is in progress.

3 General Climate Research Strategy [Long Term]

3.1 FRAMEWORK

In view of the research objectives and the status of present knowledge, two lines of research activities are anticipated.

3.1.1 Individual and Small Group Efforts

A broad range of both theoretical and empirical climate research activities dealing with all time scales is needed. These studies by individual scientists or small groups of scientists will be relatively low in cost compared with large collaborative efforts and may provide crucial ideas and insight. Broad and long-term support for these basic studies is needed because climate theory is in an early stage of development, and it is not possible to predict the timing and areas in which important advances will occur.

3.1.2 Collaborative Efforts (Focused Efforts)

Focused efforts of groups of scientists are needed in the following four areas: (1) development of a climate data base, (2) development of a climate observing/monitoring system, (3) definition and conduct of process/regional experiments, and (4) development and validation of detailed and comprehensive climate models. These studies will generally require collaborative efforts of many scientists, often including international cooperation. The studies will be relatively high in cost compared with individual efforts but can be planned to take maximum advantage of theory and observations. Progress in these four areas is an essential foundation for detailed diagnostic studies, model development, and, ultimately, sensitivity and predictability assessments.

Detailed descriptions of basic exploratory studies are best left to the individual scientist. However, it is highly desirable to outline a strategy for planning the intensive and relatively costly collaborative efforts, because they will not be done properly unless they are carefully planned.

3.2 STRATEGY FOR FOCUSED EFFORTS

The strategy for focused work in the four areas mentioned in Section 3.1 is based on our present level of understanding and the present state of the data base and the observing/monitoring system. These, to a large extent, will dictate the timetable for achieving various objectives.

The following items will be elaborated in Chapter 4.

3.2.1 Climate Data Base

Observations are fundamental to the study of climate. Most of the advances in our knowledge and understanding of the atmosphere and the ocean have been based on observations. Improvement of the present instrumental record data base is possible in the next few years and is, therefore, a high priority for immediate attention. Many of the data sets needed for climate research will also provide climate information for user applications. Therefore, efforts invested in this area should yield immediate as well as long-term benefits.

The length of instrumental records (on the order of 100 years) limits studies of climate variation to time scales up to the order of decades. Furthermore, the instrumental records are not necessarily representative of other climate regimes (glacial, as an extreme example) and may not be of sufficient length or spatial coverage to reflect extreme events adequately. Efforts must be made to develop a noninstrumental record data base. Significant improvement in this data base can be expected in the next few years. However, a long-term effort will also be required to realize the full potential of past climate studies.

3.2.2 Observing/Monitoring System

The climate observing system is required to observe the spatial and temporal variations of climate variables. Comprehensive data sets are needed for climate diagnosis, for model development and validation, and for assessment studies. The observing system can be expected to change depending on research and operational needs. The climate monitoring system is required to assure long-term records of temporal climate variability. For many climate variables, our knowledge of what constitutes a significant variation over a particular time and space scale is not sufficient to permit the design of an optimum monitoring system now. Therefore, the term *experimental* monitoring system will be used frequently in this document. The development and operation of a global climate observing/monitoring system are tasks that should involve collaboration among many nations. In this report, the overall requirements for the observing and monitoring system are outlined, and tasks that may be appropriate for the United States are suggested.

The future global climate observing/monitoring system must be a composite of space-, land-, and ocean-based systems. Three important characteristics of the climate observing/monitoring system are as follows:

1. Some observing/monitoring system components are available now, but other components will only become available later.
2. The accuracy of observing/monitoring components will improve gradually with time through a combination of sensor development, improved sampling strategy, and improved data-processing procedures.
3. Estimates of observing/monitoring requirements will depend on ongoing observational and model simulation studies as well as further comparisons between observations and climate model outputs.

The development of the observing/monitoring system will present many challenges. Observations have to be made of many hitherto largely unobserved climate variables, such as the three-dimensional distribution of clouds, the precipitation and winds over the oceans, the heat content of the upper ocean, and, eventually, the entire ocean. In many cases, not enough is known to specify time and space scales and accuracy requirements. Thus, the development of the observing/monitoring system is visualized as an evolutionary experience.

3.2.2.1 Initial Observing System

A logical first-generation global climate observing system would make optimum use of the current or near-future observing system, supplemented by new systems designed to observe, at a minimum, the largest currently known variations of climate variables. For most climate variables and for most regions, the annual cycle provides the largest variations. This first-generation global climate observing system should provide data sets that will make possible detailed studies of the mean annual climate and its mean annual variation as well as exploratory studies of interannual variations. With the start of FGGE in 1979, this system will, for the most part, be in operation. Certain portions of this system, especially the WWW and satellite-based measurements, should be continued with appropriate modifications throughout the 1980's. At the same time, steps should be taken to optimize the observing strategies (see Section 4.2 for details). The United States is supporting a significant portion of the FGGE observing system and should make a commitment to continue certain observations and data-processing tasks throughout the 1980's.

This initial observing system is best suited for observing the atmosphere and certain lower boundary conditions (land- and ocean-surface temperature, for example) as well as the radiation budget at the upper boundary (satellite-based measurements). Even for this restricted system, there will be observational gaps, for example, precipitation and soil moisture. The initial observing system will not be adequate for observing the interior of the ocean.

To support the evolving climate observing system, there should be a continuous program to develop and test new concepts, instruments, systems, and observing strategies. Such a program will also provide crucial data for filling gaps in the operational observing system and providing continuity for observations now available from experimental systems.

3.2.2.2 Evolving Observing System

As a number of years of global climate observations are accumulated with the present and near-future observing system (referred to above as the first-generation observing system), and as regional studies provide better understanding of processes and better sampling strategy, it will be possible to include more variables for observation (for example, the upper layers of the ocean) with gradual improvement in sampling strategy and accuracy. This will lead to the development of a second-generation climate observing system for the acquisition and processing of climate data sets by the late 1980's that should make possible detailed studies of interannual and, ultimately, long-term climate variability.

3.2.2.3 Timetable for the Development of a Global Observing System

With these general guidelines in mind, a timetable for the gradual development of the global climate observing system is presented in Table 3.1. The dates should be considered rough estimates. The "pacing" item for the decade may be the time required to plan and develop observing systems for the upper ocean.

The tentative timetable is based on very general assumptions about the nature of the climate system, sampling theory, and the time required for process studies and instrument development. It is assumed that much can be learned about the ocean's role in the short-term variability of climate from studies of the upper ocean. If it proves necessary to include the entire ocean column, at least in certain regions, more time will be required to develop an observing system. On the other hand, future basic research or work now in progress may lead to shortcuts that speed up the timetable. Regarding sampling theory ideas, comprehensive data sets will be needed for periods about ten times the length of the variation being studied—ten years of data for studies of the annual cycle and at least ten years for studies of year-to-year variability. Also, considerable time is required to plan, execute, and assess the required process experiments.

The tentative timetable has important implications for the sequence of detailed global diagnostic studies that can be carried out. The first-generation climate

TABLE 3.1 Tentative Timetable for Development of the Global Observing System

By 1979	World Weather Watch plus satellite-based portions of FGGE global observing system, with appropriate modifications during the early 1980's, will provide data sets that will, after some years of operation, make possible detailed diagnostic studies of the mean annual climate and its mean annual variation, as well as exploratory studies of interannual variability. There will also be a continuous program to develop and test new concepts, instruments, systems, and observing strategies.
1978–1985	During this period there will be a variety of detailed process experiments (some on-going, some proposed) aimed at defining time and space scales and/or processes of, among other things, *earth radiation budget, cloudiness, the upper ocean, and the sea ice in polar oceans*. These processes are of importance for understanding annual and interannual variations.
By 1983–1985	With knowledge gained from operational and experimental observing systems and from the detailed process experiments, it should be possible to design a "second-generation" climate observing system that will observe the upper portion of the global ocean and include other refinements as well. Data sets from this observing system, after some years of operation, should make possible detailed studies of interannual variations.
1978–1995	The "second-generation" climate observing system comes into operation. During this period there also will be variety of detailed process experiments (some on-going, some proposed) aimed at defining time and space scales and processes of the entire ocean, the slowly varying ice sheets, and other components of the climate system. These processes are of importance for understanding long-term climatic variations.
By 1990–1995	With knowledge gained from operational and experimental observing systems and from the detailed process experiments, it should be possible to design a "third-generation" climate observing system that will observe the entire climate system to some yet to be specified level of accuracy. Data sets from this observing system, after some years of operation, should make possible detailed diagnostic studies of long-term climate variability.

observing system will be best suited for detailed annual variation studies, although some gaps in the observing system remain to be filled. The first-generation system will also be suitable for exploratory studies of interannual variations. For example, it should be useful for establishing the degree to which the atmosphere responds to changes in lower-boundary conditions such as ocean-surface temperature; but it will not be adequate for understanding how the changes in ocean-surface temperature came about. By the mid-1980's, according to the timetable, it should be possible to design an observing system that will make possible detailed studies of interannual variations.

This sequential approach to detailed global observational studies (annual variation, interannual variation, and long-term variation) should in no way compromise the observational study of any aspect of climate that can and should be studied now. For example, solar irradiance should be monitored to a high accuracy now because it is of fundamental importance for climate, and a long record is needed. For the same reason, the CO_2 cycle and aerosol processes should be observed now. As a final example, studies of past climate using noninstrumental records are yielding insight into long-term climate variations. However, the sequential approach recognizes that certain portions of the observing system, especially for the oceans, will require years to develop before comprehensive global observational studies of long-term climate variation can be achieved.

In view of the urgency that may exist regarding the CO_2 buildup, it is important to stress that, if accurate estimates of climate sensitivity to this anthropogenic forcing require a detailed knowledge of long-term cryosphere and ocean responses, accurate estimates may not be forthcoming for many years. At the same time, studies of past climates may provide considerable insight into the slow physics of climate and may, to a currently unknown extent, eliminate the necessity of waiting decades or longer for accumulation of future climate data sets that might otherwise be needed to make reliable, long-term climate sensitivity estimates.

3.2.2.4 Initial Experimental Monitoring

Detailed planning for a long-term monitoring program for many climate variables is not yet possible because of our limited knowledge of sampling requirements. At the same time, it is important to continue or commence a limited experimental monitoring program now. In most cases, the experimental monitoring data will be a suitably processed subset of the data obtained from the evolving observing system. Three key concepts are as follows (discussed in greater detail in Section 4.2):

1. Continue the acquisition of climate variables where long-term records already exist and modify the observing procedure only after careful attention is given to data compatability between old and new systems.

2. Commence experimental monitoring of selected climate variables in a few selected locations even if a detailed monitoring strategy has not yet been developed.

3. Continue or commence experimental monitoring of certain external variables (solar constant, anthropogenic pollutants). Also continue experimental monitoring of certain internal variables such as components of the earth's energy budget. In this case, existing records are not extensive, but the experimental monitoring data can be obtained from the present observing system measurements.

3.2.2.5 Evolving Monitoring System

Detailed studies based on existing data sets supplemented by additional observations and process studies during the 1980's should make it possible to design a climate monitoring system during the late 1980's.

3.2.3 Development and Conduct of Process/Regional Experiments

Process/regional experiments are needed to understand basic climate processes so that they can be properly parameterized in climate models. GATE (1974) is an example of an experiment required to understand processes in the oceanic intertropical convergence zone. Because of the many processes involved in climate, a large number of process experiments will be needed in the atmosphere, ocean, and cryosphere and the upper land surface, including experiments dealing with the sources, sinks, and transports of trace gases and aerosols. The timing of process experiments will depend primarily on achieving the level of understanding required to design the experiment.

This report outlines only those process experiments that can be planned or carried out in the next five years (see Section 4.3 for details).

3.2.4 Climate Models

Climate models represent the ultimate tool for verifying our level of understanding (climate diagnosis) and for conducting climate sensitivity and predictability studies. Certain aspects of climate modeling efforts require the largest and fastest computers available and the collaborative efforts of many scientists. Several of these advanced computing facilities are needed now to deal effectively with the large amount of computing required for simulation of one or more annual cycles. The use of comprehensive climate models should proceed in highly interactive fashion with studies based on simplified models. Modeling studies, together with observational studies, will also aid in the specification and simulation of future observing systems and observing-system components. It is not clear at

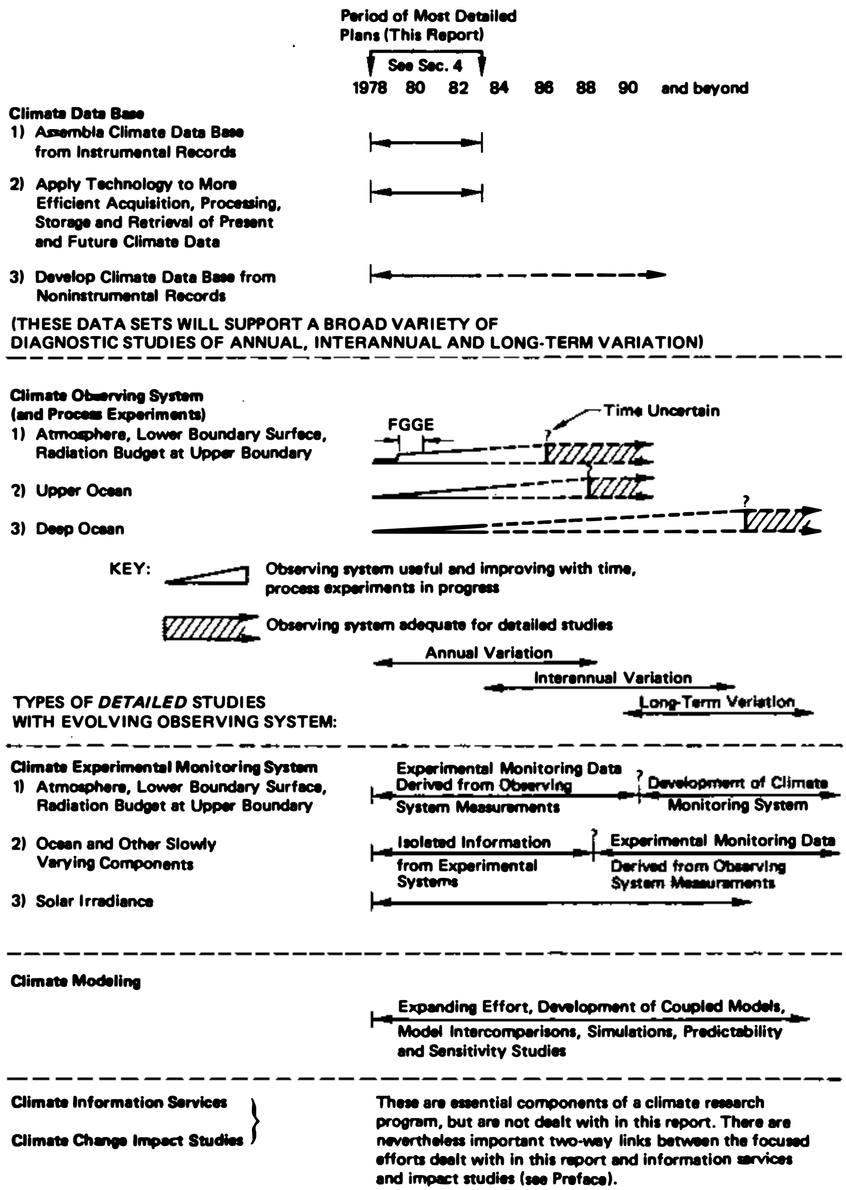

FIGURE 3.1 Timetable for focused efforts as defined in Section 3.1 and described in Section 3.2.

this point how large an effort will ultimately be required, but suggested requirements for the next five years are given in Section 4.4.

3.3 SUMMARY OF THE GENERAL TIMETABLE FOR FOCUSED EFFORTS (LONG TERM)

Figure 3.1 summarizes some collaborative efforts involving many scientists and the relatively large equipment costs of a climate research program. It illustrates the immediate tasks—assembly of a climate data base, continuation of present and near-future observing systems, and process experiments, for example—as well as the need for long-term support of the gradually developing climate research program. The previously mentioned uncertainties as to tentative dates should be kept in mind.

Also indicated is the sequence of detailed studies to be expected in connection with the evolving data base and composite climate observing system, i.e., annual, interannual, and long-term variation studies.

4
Specific Research Needs for the Next Five Years (1978–1983)

Within the framework of the long-term research strategy described in Chapter 3, an outline is now given of many of the specific research needs for the next five years (1978–1983). This refers only to large, collaborative efforts involving the development of the climate data base, the climate observing/monitoring system, the process/regional experiment, and the climate modeling capability and does not mention the broad range of research projects that need to be undertaken by individual scientists.

4.1 DEVELOPMENT OF A CLIMATE DATA BASE

4.1.1 Development of a Climate Data Base from Existing Instrumental Records

The development of climate data sets from existing instrumental records is an important immediate task. A major effort is required to assemble the data, assess data quality, and make the data sets readily available in appropriate form to scientists. For certain purposes, it will also be important to synthesize the data from different sensing systems (space, land, and ocean based and airborne) into a consistent and optimal form.

First, many of the data are not available on magnetic tape or similar storage. Quality control is important yet sometimes absent or inadequate. Second, the data sets often have not been gathered together and structured for easy use. For example, an early 12-year set of all U.S. rawinsonde observations was scattered across several hundred tapes. The National Climatic Center has recently gathered these data into logical order on about 50 tapes. The cost of gathering and preparing data is usually high compared with the cost of exchanging it. Thus, a tape costing $15 can hold the equivalent of 200,000 to 500,000 punched cards, while the keypunching of 500,000 cards may have cost $75,000. A climate study of the southern hemisphere required several man-years and about $300,000 to prepare and publish, yet the digital values are now contained on a portion of one magnetic tape.

Over the past several years, the National Center for Atmospheric Research (NCAR) has assembled, checked, and compacted a variety of climate data sets. These are now available on magnetic tape to the research community. Although these data sets are only a first step toward development of a comprehensive climate data base, they have been most useful and form a point of departure for further development. The inclusion of more climate variables, continued work on data quality control, and extension of the data set in terms of global coverage and record are now needed.

In summary, data may be available in principle; in actuality, data are often not available for easy use and exchange. The main priority, therefore, should be to obtain or create the various basic data sets. The Report of the JOC Ad Hoc Working Group on the Global Data Base for Climate Research (GARP, 1976b) can be used as a basis for further development. Three subtasks can be identified as follows:

1. *Assemble "1950–present" data set.* This set would include most of the observations of three-dimensional atmospheric structure from the radiosonde network as well as more recent satellite-based observations (target date for completion: 1983).

2. *Assemble "long-term instrumental record" data set.* In selected locations, instrumental records from the atmosphere, ocean, and land surface go back to the 1800's and, in a few cases, the 1700's. While not global, these records are valuable for estimating time and space scales of natural variability and for exploratory studies of processes (target date for completion: 1983).

3. *Assemble "compressed" FGGE data set.* The FGGE data set will provide the most detailed picture to date of one annual cycle. The above-mentioned JOC document defines the content of the compressed set as consisting of the time- and space-averaged statistical properties of all the FGGE data sets (target date for completion: 1980–1981).

A working-level group (or groups) should be constituted as soon as possible to advise the government on priorities for specific tasks within these three categories. Certain data sets can serve both research needs and the needs of users of climate information. It is, therefore, important to be aware of the needs of both research and user communities in order to optimize the data processing.

4.1.2 Applications of Technology to More Efficient Acquisition, Processing, and Retrieval of Present and Future Climate Data

There is an immediate need to apply available technology to problems of data acquisition, processing, and retrieval. The tremendous volume of data for climate research is currently overwhelming the data system. For example, certain meteorological satellite signals are not being routinely processed or stored, and large numbers of bathythermograph recordings have never been processed. Without significant improvements in the data-management area, the increased data flow will not be handled properly. The following possible developments are noted:

1. Use of modern technology such as microprocessors to extract climate information from the real-time data flow. For example, certain space- and time-averaged statistical properties of the satellite radiation measurements could be automatically acquired. The climate information could be derived from the composite observing system as well as from individual components of the observing system.
2. Increased use of satellite communication links to acquire data from remote locations.
3. Use of modern data storage, retrieval, and display systems.
4. Use of multiterminal links to these systems and to large computers.

In all of these possible developments it will be important to link the technological aspects of data management with scientific uses so that data sets of high quality and utility can be obtained. This will require investment in scientific manpower as well as electronic hardware (target date for implementation: 1983).

4.1.3 Development of Climate Data Sets from Noninstrumental Records

The general rationale for this work is developed in Section 3.2. Currently, there is considerable research in this area; but the task is large, and long-term support will be required. Some of this work will be done by individual scientists, but some will involve large collaborative efforts. The CLIMAP project is an example of a large, interdisciplinary effort to define the global climate at specific times in the past.

Highest priority should be given to the assembly of the following past climate data subsets:

1. The past 1000 years (for studies of climate variation on time scales of 10 to 100 years). This interval provides the possibility of year-by-year chronology

in certain parts of the climate system over a time span that overlaps the instrumental record.

2. The past 30,000 years (for studies of climate variation on time scales of 100 to 1000 years). This interval is chronologically controlled by ^{14}C dating. The response of many parts of the climate system during a major climate change (glacial–interglacial) can be studied.

3. The past 1,000,000 years (for studies of climate variation on time scales of 1000 to 100,000 years). This interval has a reasonably good chronological control and a well-developed global record of changes in the ocean. Changes in global climate that appear to have a significant cyclic component can be studied.

These climate periods and time scales are most relevant for the program objectives in climate diagnosis, predictability, and sensitivity. The climate history of planet earth prior to several million years ago is certainly of interest and should be supported on its own merits, but several reasons suggest that it should not be given high priority now for purposes of this program. First, with increasing age, the climate record becomes progressively more fragmented, more difficult to read and to quantify, and loses temporal resolution. Second, the older records provide insights mainly into the climate effects of changes in boundary conditions that occur very slowly, for example, changes in a continent's position. Third, the opportunities for paleoclimatologists to interact with physical climatologists and to employ conceptual and numerical models of modern climate are more numerous in dealing with the recent past.

The immediate task is to develop a more detailed plan for the gradual assembly of the data set most useful for meeting objectives of this program (Section 1.1). For each of the data subsets defined above, guidelines must be established for time and space sampling rates and accuracies. It will also be necessary to assess the resources required for field work, isotopic dating capabilities, and chemical and biological analysis capabilities. Long-term support of this work is required because the task cannot be accomplished in a few years. International collaboration will be essential (target date for a detailed plan: 1979).

4.2 DEVELOPMENT OF AN OBSERVING/MONITORING SYSTEM

4.2.1 Atmosphere, Lower Boundary, and Upper Boundary

4.2.1.1 Initial Observing System

The FGGE will provide the most detailed set of observations of one annual cycle ever assembled. The continuation and gradual improvement of certain portions of the FGGE observing system will take maximum advantage of the experience and costs involved in developing this system.

It is not our intent to list every variable that should be observed, and it is recognized that certain systems, such as ships and planes, will not be kept in operation. The initial climate observing system for the 1980's would consist primarily of the WWW observations plus a continuation of the operational and research satellite observations planned for FGGE. The list would include:

1. WWW observations of pressure, temperature, humidity, and wind.
2. Observations of pressure, temperature, and wind from large commercial jet aircraft (Aircraft Integrated Data System, and Aircraft to Satellite Data Relay).
3. Indirect temperature and moisture soundings and cloud-motion winds from satellite-based observing systems.
4. Earth radiation budgets from satellite-based systems.
5. Ocean-surface temperature.
6. Sea-ice and snow extent.
7. Precipitation.
8. Land temperature, soil moisture, and surface albedo.
9. Runoff from major rivers.
10. CO_2, O_3, and aerosols.

A combination of surface- and space-based observing systems may provide the best estimates for each of these variables.

Some further development work is required to increase the accuracy and representativeness of most of these observations. However, even the present systems are useful for a "first look" at climate on a near global scale. It will also be necessary to maintain and to continue development of the proper analysis procedure for integrating these diverse data sources into a consistent and best estimate of the actual state of the atmosphere–ocean–cryosphere–land surface system. This will imply a continuing and major data-processing task through the 1980's.

To support the evolving climate observing system, there should be a continuous program to develop and test new concepts, instruments, systems, and observing strategies. Such a program will also provide crucial data for filling gaps in the operational observing system and continuity for observations now available from experimental systems.

4.2.1.2 Initial Experimental Monitoring

Some subset of the data from the initial atmosphere and lower- and upper-boundary observing system can serve as initial experimental monitoring data.

Since data from the observing system will be stored for research work, there should be little additional cost associated with experimental monitoring. It will be necessary, however, to identify an appropriate subset of the observations (taking into consideration best estimates of temporal and spatial sampling requirements) and to designate the subset as benchmark observations. Any change in location or operation of the observing system must be carefully planned to maintain continuity and representativeness of these benchmark observations (target date for identification and designation of benchmark observations: 1980).

While some subset of observations from the current observing system can serve as initial experimental monitoring data, a study of the feasibility of constructing a system designed specifically for climate monitoring purposes should commence. The current observing system has evolved in response to weather forecasting requirements and is by no means designed or located optimally for long-term climate monitoring. It may be possible to design a monitoring system by the late 1980's, based on results obtained from the initial operational and experimental observing system as well as the results of process experiments (target date for completion of initial study: 1983).

4.2.2 Ocean

4.2.2.1 Initial Observing System

The present and near-future observing system for the ocean consists of continued observation of ocean-surface temperature using satellite techniques, continued use of ship reports, and continued or expanded measurement of sea level from tide gauges at island and coastal stations. Drifting buoys are already being used in some regions, and a sizable number will be deployed during FGGE. However, it is too early to recommend that drifters be part of the standard ocean observing system for the 1980's. This will depend on their usefulness as demonstrated during drifter experiments in the next few years, including FGGE.

Efforts should start now on the long-term task of developing techniques for observing the ocean's three-dimensional structure and behavior.

4.2.2 Initial Experimental Monitoring

Ocean monitoring for climate falls into the following two categories:

1. A mix of experimental monitoring programs, each of which is relatively limited, but the sum of which will be cost-effective.
2. Long-lead-time tasks to develop techniques for observing the ocean's structure and behavior (mentioned above).

With the exception of some coastal and island tide gauge stations, long-term series are almost nonexistent. Thus, the main priority is some long-term commitments to measurements in a relatively few regions, those regions to be chosen on the basis of the best estimate of the dynamical importance of the region.

Our uncertain knowledge of the actual nature of the ocean–atmosphere interaction makes it difficult for us to determine how far below the surface our experimental monitoring program must go and what variables are essential. Uncertainties about the horizontal scale of such monitoring and the frequency of sampling also exist.

The results obtained from the initial experimental monitoring data can be used for various empirical data correlation studies and to establish the importance of the various stations. These data can then be used, together with the data from the various process experiments, to determine the next step toward a global ocean observing/monitoring system.

Listed below are four types of experimental monitoring that could be implemented now.

1. *Ships of Opportunity and Phantom Weather Stations.* These are merchant ships that make routine observations along regular routes. The advantages are a regular network of repeated sections, coverage of large areas, and relatively low cost. The disadvantages are that data are concentrated along the main shipping routes, and large areas are uncovered. The NORPAX program has made good use of this type of data for the equatorial and North Pacific. The "phantom weather station" concept also depends on the use of commercial ships for data collection. Several routes worked by major fleets cross hydrographically critical and representative sites. If observations could be arranged at these sites, then a fixed-point data-collection network could be established. In this concept, the major carriers would be responsible for one or two stations, which they alone would occupy and which would be located at the most favored location along their most traveled route. The existing network of routes suggests that up to 100 such stations could be established.

2. *Island Stations.* Tide-gauge records and sea-level records from coastal stations and islands have proven enormously important in establishing empirical air–sea interactions and teleconnections and represent some of the longest records available. It is important that the current records be maintained. The addition of sea-level measurements to all islands in representative midocean areas is probably the most cost-effective next step toward a global ocean monitoring system that could be taken. The technology for reliable automatic surface weather measurements with satellite readout is near, and all representative island stations should be equipped with automatic sea-level gauges and weather stations with satellite readout.

3. *Moored Arrays.* To determine variability below the surface, it will be necessary to maintain a few deep moorings in representative areas. These should be simple subsurface moorings with the most reliable equipment. Examples of areas of particular importance are the equatorial region, midgyre region, and a subpolar region. As a specific example, a deep mooring could be placed in the main thermocline at 1000 m near Bermuda with two Aanderaa current meters. The mooring could be replaced once a year for a period of five years. Such data, together with the Panuliris hydrographic series, would be invaluable for a record of variability in the mid-Atlantic.

4. *Repeated Hydrographic Sections.* Recent work is beginning to show that sufficiently detailed hydrographic data, with a few direct current observations, may be sufficient to establish the ocean circulation variability. To further test this possibility, a series of repeated hydrographic sections across selected areas of the ocean is needed. For example, a section could run from Woods Hole, Massachusetts, to Bermuda and from Bermuda to Miami, Florida, to establish the variability of the hydrographic field over a period of several years. Such a program should start with three to four sections per year. The analysis of these data would then indicate how often the section needed to be repeated.

4.2.3 Ice

4.2.3.1 Initial Observing System

The current and near-future observing system for the cryosphere consists primarily of satellite remote sensing of sea ice and snow cover. In addition, a network of air-deployable buoys should be operated in the Arctic Basin. This network will first operate during FGGE (1979) as part of the POLEX program. It will make possible the observation of sea-ice drift patterns. Ice deformation, especially divergence, has a large influence on the heat exchange between ocean and atmosphere and on ice production. To observe year-to-year variability, it will be important to maintain this buoy network for at least one decade (the 1980's). These buoys should be equipped with locating devices and sensors for atmospheric pressure and temperature. At least ten buoys should be in operation at all times.

4.2.3.2 Initial Experimental Monitoring

Only through long-term measurements will data be obtained to understand whether ice dynamics plays a positive, negative, or neutral feedback role in climate. Thus, a subset of the sea-ice and snow-cover observing-system measurements will be required for long-term monitoring.

For long-term changes, the continental ice sheets should be monitored. Recent field results from Antarctica and Greenland and advances in ice-sheet modeling suggest that any major ice drainage basin may be capable of surging. Such surges would inject great masses of glacial ice into the ocean that, in turn, would produce global sea-level changes and, perhaps, climate changes. In view of the potentially enormous global impact of such an event (or events), monitoring should begin now. A modest program would include long-term monitoring of the height of the ice sheets along a few selected profiles and the horizontal displacement of several points on the surface. A sampling rate of once per year is adequate. Satellite techniques to do this are available. At the same time, detailed process studies that may lead to better understanding, modeling, and monitoring strategies are needed.

4.2.4 External Variables

The sun is the energy source that drives the climate. There is ample evidence of the variability of energy flux in the short-wavelength portion of the solar spectrum and some evidence, more uncertain, of variability in the total energy flux. Observational studies of solar weather–climate relationships and climate model sensitivity studies both suggest that the climate may be sensitive to rather small variations in this fundamental external variable. It will be important, therefore, to continue and refine our monitoring of the solar flux, including the establishment of sampling requirements. The total solar irradiance should be measured to at least 0.5 percent relative accuracy by the mid-1980's. The solar ultraviolet flux (1800–3100 Å) is particularly important for studies related to ozone absorption in the stratosphere and should also be monitored in coordination with ozone studies.

4.3 PROCESS/REGIONAL EXPERIMENTS

All processes discussed here are listed in Table 4.1.

4.3.1 Atmosphere and Lower Boundary Processes

4.3.1.1 Atmospheric Dynamics and Energetics, and Coupling with Lower Boundary: FGGE, MONEX, POLEX, and GATE

The FGGE will provide a useful data set for the detailed global study of large-scale atmospheric motions. Such questions as the interaction between tropical or subtropical and midlatitude circulations, interaction between midlatitude and polar circulations, and cross-hemisphere couplings will receive detailed study. Because the experiment covers an entire year, the data set will permit study of one annual cycle with, for the first time, a fairly complete set of atmospheric, lower-boundary–land, ocean, and ice surface–and upper-boundary radiation budget measurements.

On a regional scale, the MONEX will permit detailed study of monsoon processes that are central to the problem of the seasonal cycle. In high latitudes, the POLEX will provide opportunities for detailed study of the polar atmosphere and its coupling with the lower boundary and midlatitudes.

In summary, support for the observational phase of FGGE and its various subprograms (MONEX and POLEX, for example), along with follow-up support for thorough analysis of the data, should be very-high-priority items for climate research.

Although the operational phase of GATE was completed in 1974, there is a continuing need to support the analysis of the GATE data because it will be necessary to incorporate the effect of tropical convection in climate models. While GATE concentrated on tropical ocean convection, it may also be important to make detailed studies of convection over tropical continents.

TABLE 4.1 Intensive Studies of Climate Processes

1. Atmosphere and Lower Boundary Processes
Atmospheric dynamics and energetics
Cloud-radiation dynamic interactions
Earth radiation budget
Land-surface processes
Carbon dioxide
Ozone and other radiatively important gases
Aerosols
2. Ocean Processes
Tropical air–sea interaction
Midlatitude air–sea interaction
Meridional heat flux
Ocean–ice interaction
Geochemical exchange
3. Ice Processes
Arctic Basin sea-ice dynamics
Antarctic sea-ice dynamics
Polar planetary boundary-layer processes
Ice-sheet dynamics

4.3.1.2 Cloud-Radiation Dynamic Interactions

The importance of horizontally extensive, persistent tropospheric stratiform clouds in modulating the earth's radiation budget is widely accepted. However, improved understanding of cloud-radiation budget–climate interactions requires a knowledge of not only the radiative characteristics of the clouds but also their spatial and temporal extents and the physical and dynamical processes responsible for their formation, persistence, and dissipation. The studies must deal with both low-level stratiform clouds, including marine stratus and stratocumulus, and upper-level stratiform clouds, particularly cirrus and altostratus. Both modeling and observational studies are required.

The precise design of the observational studies remains to be determined. The observational effort must attempt to define the physical characteristics and thermodynamic and dynamic structures of not only the cloud itself but also the large-scale environment around it. Observation systems should include aircraft, ships for marine stratiform cloud studies, rawinsondes, lidars, satellites, acoustic sounders, and radiometersondes.

The areal and temporal extent of major stratiform cloud systems must also be determined. These observations can be accomplished primarily from satellite and lidar observations. Some statistical information on the radiative characteristics of the clouds may also be derived from this data set.

A rather complete understanding of the behavior and radiative characteristics of tropospheric stratiform clouds should emerge from these studies. Then, physically consistent parameterization techniques may be developed to investigate cloud radiation–climate interactions in both prognostic and diagnostic models.

This research is feasible using 1977 technology. Furthermore, it can be accomplished largely within or near the continental United States, because the cloud phenomena occur frequently over or near the North American continent, the scientific expertise for the various elements resides within the United States, and the aircraft and instrumentation capabilities are largely dominated by the U.S. scientific community. The experimental phase could rely heavily on the National Weather Service rawinsonde network thereby largely eliminating the need for additional, costly rawinsonde equipment. High-altitude capability aircraft from NCAR, the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, and the Department of Defense could provide the airborne platform for many of the observations.

4.3.1.3 Earth Radiation Budget

The basic components of the earth radiation budget are the solar input at the top of the atmosphere, the reflected solar radiation, and the emitted long-wave radiation from the earth-atmosphere system. To study the details of the earth radiation budget, it would be highly useful to have the radiative fluxes at the earth's surface, including the oceans as well as at the top of the atmosphere. From these two basic components, one can determine the distribution of absorption of solar radiation between the atmosphere and the earth's surface, the magnitude of the greenhouse effect, and part of the total surface heat budget. Determining the influence of clouds in regional heat distribution and the effects of changes in land use, vegetation, and snow cover is equally important. Comprehensive studies of the earth's radiation budget require intensive regional and global observations on a scale possible only through extensive use of satellite technology in addition to ground observations. Satellite-based observations of the earth's radiation budget began in the 1960's and have contributed greatly to our present knowledge of global climate. As more sophisticated radiation budget experiments are planned and conducted, it will be important that the test program (see Section 1.2, Recommendation 6) be used to continue testing of new instruments and observing strategies, including the use of multiple satellite platforms, so as to achieve the best possible earth radiation budget observing system by the late 1980's (second-generation climate observing system).

4.3.1.4 Land-Surface Processes

Aspects of the moisture budget and energy budget at the land surface are inadequately treated in numerical models. Adequate data sets for surface radiative fluxes, surface and subsurface temperature and moisture, surface roughness, surface albedo, and precipitation and runoff are not available. It will be necessary to study these processes on rather large scales (the scale of major watersheds such as the upper Mississippi, for example). Planning for these process experiments should be started.

4.3.1.5 Carbon Dioxide

Changes in the atmospheric concentration of CO_2 depend on an interplay between the atmosphere, the land biota, the soil, and the ocean. Man's use of fossil fuels is currently injecting CO_2, other trace gases, and aerosols into the atmosphere. Because of its importance in atmospheric radiation transfer, atmospheric CO_2 concentration is an important factor in global climate. The climate response may be complex because of internal feedbacks. The problem posed by increasing atmospheric CO_2 concentrations is thus inherently complex and multidisciplined. The WMO has proposed a research and monitoring project on atmospheric CO_2. The United States could make a major contribution to this project.

4.3.1.6 Ozone and Other Radiatively Important Gases

Absorption of solar ultraviolet radiation by ozone is responsible for the heating of the atmosphere above 30 km. Changes in the distribution of ozone or other trace gases can affect the troposphere because the stratosphere and troposphere are coupled both radiatively and dynamically. A study of the life cycles of these gases, their radiative effects, and the resulting impacts on climate is needed.

4.3.1.7 Aerosols

At the thirteenth session of the JOC the following four major studies were recommended: (1) definition of the basic aerosol types so that a world climatology of aerosols can be developed; (2) an observational program adequate for a quantitative description of the source, dispersion, and sinks of atmospheric aerosols; (3) design of field experiments to measure radiative properties of aerosol types relevant to climate; and (4) design of a numerical experimentation program to assess the role of aerosols for the radiative fluxes in general circulation models and to get some preliminary views on their importance for climate.

4.3.2 Ocean Processes

The ocean plays three major roles in the global heat balance. It releases or accepts heat from the atmosphere, it stores heat, and it transports heat from place to place. The ocean is the most important medium to store heat, at least on a seasonal time scale, and this property leads to a significant moderation of the seasonal extremes from what would exist in the absence of such heat storage. Moreover, ocean processes are important in the global geochemical exchange system, for example, the storage and exchange of CO_2.

4.3.2.1 Tropical Ocean-Atmosphere Interaction

In tropical regions, the ocean heat storage and transport and the ocean-atmosphere coupling play an important role in the annual climate cycle. Monthly-to-interannual variability is high, and atmospheric general circulation models show a remarkable sensitivity to oceanic conditions near the equator. Models and observations of tropical ocean variability suggest that low-frequency changes in the trade winds induce transients in the transport of currents in the central tropical ocean. These transients, in turn, result in anomalous conditions, like the El Niños, in the eastern tropical oceans. The redistribution of heat by ocean currents appears to be one major mechanism in the establishment of large-scale oceanic heat anomalies both in the central equatorial ocean and along the eastern boundary.

Equatorial ocean climate programs must focus on the large-scale, low-frequency variability of oceanic advection, which redistributes heat stored in the surface layers of the ocean. Although there is a need for concentrating some of the effort in dynamically important regions, the overall program must be aimed at an understanding of how the fluctuations and anomalies in all the various components of the equatorial current system are related to atmospheric forcing, both local and more removed. In the Indian Ocean, the relation between the equatorial circulation and the western boundary current must also be a part of such studies.

4.3.2.2 Midlatitude Ocean–Atmosphere Interaction

In the northern hemisphere, the ocean-to-atmosphere heat flux is maximum off the east coasts of Asia and North America at about 40° N. The strong thermal gradients at the cold boundaries of warm ocean currents create strong horizontal differences in the heating of air over these regions. Displacements of the current boundaries and the corresponding anomalies of heat storage and sea-surface temperature could be related to atmospheric circulation anomalies. At the seasonal time scale, heat storage in the midlatitude upper ocean leads to a significant moderation of the seasonal climate cycle, with the midlatitude ocean acting as a major heat source in winter and as a heat sink in summer.

Initial studies have revealed that the scales of variability associated with the thermal structure of the North Pacific are of the order of years and several thousand kilometers, that anomalies with a magnitude of 1–2°C can develop suddenly over a period of a few weeks and can last for years, and finally, that the midlatitude sea-surface temperature anomalies appear to be surface signatures of disturbances that extend well into the permanent thermocline. Field and theoretical studies to describe and understand the formation and evolution of climate anomalies and related changes in the general ocean circulation are required to assess the role of these large-scale midlatitude processes in climate dynamics.

As a basis for large-scale studies, a knowledge of the physics of the formation and deepening of the mixed surface layer and its interactions with the atmosphere is important. Such processes are "subgrid" scale for numerical climate models, and parameterization of these processes in terms of large-scale variables is required. However, the processes of interaction of the atmospheric and oceanic boundary layers is understood only in a limited sense. Measurements of surface stress, evaporation, and heat transfer have been limited to low wind speeds, whereas much of the transfer probably occurs at high wind speeds. Moreover, the static stability of the atmospheric boundary layer strongly affects vertical transfer. For these reasons, vertical transfer over the sea must change dramatically with the passage of cold fronts, and large magnitudes of vertical flux must be associated with these fronts.

A number of possible mechanisms by which air–sea interaction processes might significantly influence synoptic-scale convergence in the boundary layer and the large-scale circulation are listed below as examples of processes that are central to a field research program devoted to this problem:

1. The relation of boundary-layer convergence to the distribution of the air–sea temperature difference.
2. The role of boundary-layer mesoscale convergence and divergence in the vertical transport of water vapor and other aspects of the interaction of the boundary layer with the free atmosphere in ocean cyclones.
3. Ekman-induced enhancement of pre-existing thermal gradients in the ocean surface could increase the existing baroclinicity in the atmospheric boundary layer and the lower troposphere. This may have consequences for the dynamics of mesoscale boundary-layer systems and for larger-scale synoptic systems.

Experiments to test these hypotheses should follow the studies of the Barbados Oceanographic and Meteorological Experiment (BOMEX), the International Field Year of the Great Lakes (IFYGL), GATE, the Air-Mass Transformation Experiment (AMTEX), and the Mixed Layer Experiment (MILE) and complement the ongoing work of the Joint Air–Sea Interaction Experiment (JASIN) and NORPAX. The problem is to get measurements during strong winds, because transfers are proportional to wind speed squared or to an even higher power.

4.3.2.3 Meridional Heat Flux

Recent determinations of the earth's heat balance from satellite-measured radiation flux and from estimates of atmospheric meridional heat fluxes from upper-air measurements have shown, via a residual calculation, that the ocean carries a significant share of the meridional global heat flux, e.g., the ocean carries over half of the total ocean–atmosphere heat flux at 20° N. In order to incorporate the phenomena of oceanic heat flux properly into global climate models, a better knowledge of how and where the heat is actually transported needs to be developed. The following types of heat transport are all potentially important: transport by the mean circulation in horizontal gyres, transport by the mean circulation in vertical meridional cells of the abyssal circulation, and transport in the surface layers of the ocean.

A monitoring program for ocean heat flux has not yet been established. The present lack of *in situ* observations of the major ocean transports (heat, angular momentum, and water) and the consequent lack of knowledge of the processes responsible must be regarded as primary problems for the future. By initiating the proper pilot studies now, the needed information could be acquired over the next few years to launch an observational study of the poleward fluxes in the ocean across latitude circles in the neighborhood of 20° N.

Two projects now emerging that could gather information important to the design of a pilot heat-flux study are a study of the interior variability of the subtropical gyre, which could be conducted in either the Pacific or the Atlantic Oceans, and a study of the mesoscale variability of the western boundary region of the western North Atlantic and Gulf Stream, a logical continuation of the Polygon Mid-Ocean Dynamics Experiment (POLYMODE) and other studies of the Gulf Stream system.

An experiment to study heat transport in subtropical gyres can focus initially on two aspects: hydrographic monitoring of the interior of the gyre and monitoring of the poleward heat transport of the Gulf Stream in shallow shelf areas of high vertically averaged temperature. Such an initial program assumes that the geostrophic and surface-layer contributions to the heat flux in the gyre are nearly equal and opposite—as the data seem to show for the mean in both the Atlantic and the Pacific. However, data and model studies suggest that seasonal variations of wind stress can lead to large variations of heat transport that are not compensated by adjustments in the geostrophic flow. Transport variations indicate that the heat flows from the summer hemisphere to the winter hemisphere. For a proper seasonal variation study, therefore, it will be necessary to monitor all components of the heat flux. This must come after an adequate knowledge has been gained from the studies proposed above.

The effect of western boundary currents on the ocean heat flux is not limited to a mean transport. Our present evidence is that the western boundary currents such as the Gulf Stream are sources for mesoscale eddies. Eddies can affect the general transport of heat in two ways: directly by eddy transport and indirectly by driving rectified flows. It has been suggested that the deep gyre driven by eddies beneath and offshore of the Gulf Stream is effective in reducing the heat advected poleward by the Gulf Stream itself. Such changes would have major effects on the global heat flux; thus, this somewhat unexpected feature of the Gulf Stream requires investigation. It is intimately connected to the dynamics of the eddy regime.

4.3.2.4 Ocean-Ice Interaction

The heat flux and sea-surface temperature anomalies are linked in the polar regions where the prime climate problems are the processes that control the edge of the ice and the ice concentration. The large albedo and insulation changes associated with the change to ice have a major seasonal and interannual effect on the heat balance in the polar regions. For example, the effective size of Antarctica doubles from summer to winter. In spite of an ability to monitor the edge and concentration of the ice, very little is known about the processes that control those changes. The upper ocean is a major determining factor because the heat supplied from below determines whether the ice freezes or melts. A second factor in polar regions is the amount of ice carried by the surface currents. In the Arctic, the amount of ice carried out of the Arctic Basin is as important in the overall heat budget as is the amount of heat carried by the ocean currents. Both upper-ocean experiments in the vicinity of the ice edge and more modeling of the processes are needed.

4.3.2.5 Geochemical Exchange

An example of geochemical exchange important to climate is the CO_2 problem. As pointed out in the report *Studies in Geophysics–Energy and Climate* (Geophysics Research Board, 1977b), success in estimating atmospheric CO_2 levels over the coming decades depends, among other things, on being able to estimate the fraction of fossil-derived CO_2 that will remain in the atmosphere. The ocean is an important factor because it absorbs more carbon than the land biota. Further field and theoretical studies are necessary to improve the one-dimensional ocean exchange and mixing models now used for determining CO_2 levels in the ocean. The Geochemical Ocean Section Study (GEOSECS) and proposed transient tracer studies are a basis for such work.

4.3.3 Ice Processes

A priority problem in short-term ice processes relevant to climate is the role of sea ice in the coupled atmosphere–ocean system. The objective is to parameterize sea-ice dynamics and related atmospheric and oceanic processes in climate models. Such studies are part of the GARP Polar Subprogram. The specific objectives of the program are to measure the large-scale motion of the sea-ice pack in the Arctic and the Antarctic and to use these results to improve existing models of ice dynamics. In addition, boundary-layer processes in both the atmosphere and the ocean will be measured in the presence of the ice, and the large-scale energy exchange will be estimated. The GARP Polar Subprogram will be international, will involve several institutions and agencies from the United States, and is expected to begin during the FGGE and continue throughout the 1980's.

Certain important aspects of sea ice–ocean coupling were dealt with in Section 4.3.2. The possibility of ice sheet surging was mentioned in Section 4.2.3 along with recommendations for initiating a long-term monitoring program of the continental ice sheets. It will also be important to develop process studies to aid in the refinement of ice-sheet modeling and monitoring strategies.

4.4 MODELING STUDIES

Modeling studies play a central role in climate research because only through them can an understanding of the underlying dynamics of the climate system be acquired. Models may be used to examine the relative roles of various physical processes in the maintenance and change of climate, the sensitivity of the climate to changes in boundary conditions or parameterization, and the predictability of specific climate events. Because so little is known of these aspects, it is extremely important that a vigorous climate modeling effort be supported on a long-term basis. As the program develops, models will be the primary tool for experimental predictability studies (monthly, seasonal, and longer time-scales), senstivity studies (climatic effect of CO_2 buildup, for example), and periodic assessment of our capabilities in these areas. Modeling studies, together with observational studies, will aid in the specification and simulation of future observing systems and observing-system components.

The relative advantages of the many different climate modeling approaches are not sufficiently known. Therefore, a wide variety of models, including those of widely differing resolution and degrees of statistical parameterization, should be developed and applied to appropriate aspects of the climate problem. Particular attention should be given to the systematic comparison of the climate simulation capability of the various models, to the design of new climate models of maximum computing efficiency, and to the means for verifying model results on data sets of comparable temporal and spatial resolution.

Increased efforts should be made to apply present models to the simulation of the annual cycle, to the simulation of specific climate events such as monsoons, and to the further exploration of the climatic consequences of man's alteration of the natural environment, such as the increase of atmospheric CO_2 from fossil-fuel combustion and the large-scale alteration of surface albedo. Increased attention should be given to the problem of atmosphere–ocean coupling, with the aim of devising more efficient and appropriate representations of the exchanges of heat, moisture, and momentum on a variety of climate time scales.

Model validation is an important and difficult task. There are many measures useful in validating climate models, for example, comparison with observations and with more elaborate, but less flexible, models that have been validated. The requirements for validating atmospheric general circulation models are complex and should include the ability to simulate typical atmospheric structures and to reproduce both observed and mean values and the degree of day-to-day variability in different regions of the globe, all with a minimum of adjustable parameters. Areal precipitation is a sensitive indicator of model fidelity. Tests of specific aspects, such as cyclone dynamics or the parameterization of cloudiness, can be made in a short-term forecast mode. Verification of radiation balances requires regional budgets of ocean heat storage and net radiation to space. Maintaining these balances through different seasons is a stringent standard that, once attained, would greatly enhance confidence in the results of sensitivity experiments.

It is envisaged that many groups will participate in various aspects of the modeling studies. The complexity and number of the problems requiring early attention to diagnostic, sensitivity, and predictability studies require that special emphasis be given to the climate modeling problem. It is, therefore, recommended that appropriate computing capabilities be available for modeling efforts focused primarily on various aspects of the climate problem. Computing support, including support scientists, is especially important for those scientists not having easy access to the largest and fastest computers. The development of comprehensive climate models is a labor-intensive activity; therefore, long-term support of at least a core of the relatively large scientific staffs will also be required.

Support of the climate modeling effort should be sufficient to ensure the timely execution of modeling studies with the most advanced models available and to contribute valuable guidance to the climate program through systematic intermodel comparisons and simulation studies. While the primary tool for climate modeling is the numerical model, laboratory experimentation using the rotating annulus and "dishpan" case provided significant insight into fundamental problems of geophysical fluid dynamics and should be considered one component of the climate models referred to frequently in this report.

4.5 GOALS FOR THE NEXT FIVE YEARS (1978–1983)

The progress to be expected during the next five years for climate diagnostic studies, predictability studies, and sensitivity studies is briefly summarized below.

4.5.1 Climate Diagnostic Studies

1. Improved knowledge of the average seasonal cycle based on analysis of pre-FGGE, FGGE, and post-FGGE data sets.
2. Improved knowledge of time and space scales and processes of past climate variation based on analysis of noninstrumental records.
3. Improved capability for modeling the average seasonal cycle, including coupled models of the seasonal cycle.

4.5.2 Climate Predictability Studies

1. Improved knowledge of the degree to which the interannual variations from the average seasonal cycle are related to certain measurable physical variables such as conditions at the lower boundary, e.g., ocean-surface temperature and soil moisture. This goal would be only the first phase of a two-phase process. A second phase would be required to establish methods of predicting such variables as ocean-surface temperature. If such variables can be identified, the second half of the 1980's would focus on studies predicting these variables with the aid of an improved observing system.

2. Improved knowledge of ocean processes, especially upper-ocean processes. Information should become available to design an observing system for the upper ocean.

3. Improved capability for simulating interannual variations and conducting predictability studies using coupled models, but it is too early for a detailed assessment of prediction capability.

4.5.3 Climate Sensitivity Studies

1. It is hard to foresee what progress will be made in the next five years in improving our knowledge of the degree to which climate is sensitive to prescribed human or naturally produced changes. This is because our knowledge of the response, including the long-time-scale response, of the fully coupled climate system—atmosphere-ocean-cryosphere-land surface—might not improve markedly in this time span. However, it is expected that our improved knowledge of the seasonal cycle, as determined from the initial observing system, will be used for the validation of seasonal cycle simulations for a hierarchy of climate models. This is viewed as a stringent standard that would greatly enhance confidence in the results of sensitivity experiments.

2. Improved understanding of the behavior of various components of the climate system important for climate sensitivity studies can be expected (CO_2 processes, ozone processes, aerosol processes, deep-ocean processes, and long-time-scale processes as diagnosed from studies of past climate).

3. Improved capability for simulating long-term climate variations and conducting sensitivity studies using coupled models can also be expected, but it seems much too early for a detailed assessment of capability to make sensitivity estimates.

4.6 IMPLEMENTATION

4.6.1 Research Staffing

Recent manpower surveys suggest that the disciplines on which climate research already draws have a relatively strong manpower base. There is a need for increased entrainment of young talented workers from these fields to climate research. One mechanism might be through a program of postdoctoral fellowships and internships. Another manpower source stems from those already established scientists who are turning their attention to climate research. It has been stressed throughout this report that climate research will involve a long-term effort. Therefore, the graduate-student training programs at the universities need to be maintained and strengthened.

The expansion of climate research opportunities is occurring at a time when the number of university faculty positions has stopped growing. One way for university professors to augment their research efforts and, at the same time, make use of the available manpower pool is through increased federal research support for university research staff (project associates, support scientists, for example). To be most effective, this should be in the form of continuing support (for example, five years at a time). A modest start now in this direction is recommended, with expansion or contraction as appropriate.

It will also be important to maintain and to further develop ties between the agencies involved in various aspects of climate research, such as NOAA and NASA, and the entire research community. One way to encourage increased involvement is for these agencies to make contracts or grants to outside scientists to carry out portions of the agencies research programs. It is also vital that there be extensive two-way exchange programs between government agencies and universities. Agencies need academic experts for both short and extended terms and, in the other direction, universities would benefit from having agency scientists in residence. These exchange programs would be another important way to ensure close collaboration and integration.

4.6.2 Program Coordination

The climate research program will require strong national and international cooperation and coordination. The national climate research program is of such scope and magnitude as to require the efforts of all agencies having relevant expertise and resources. Therefore, the program should be coordinated at a sufficiently high government level to ensure that all agencies contribute appropriately in a collaborative mode. There should also be a formal mechanism by which university, government, and industry scientists can work together in planning and carrying out various tasks and programs needed to achieve the objectives.

Consideration should be given to the establishment of a Climate Council with the following functions:

1. To serve as the focal point within the United States for the development of a global research and action program.

2. To coordinate activities that cross disciplinary, institutional, and organizational boundaries.
3. To serve as a link with international mechanisms that guide international research and action programs.

At the international level, it is important to re-emphasize that the United States can contribute only a portion of the research funds and talent required for the World Climate Program and that active and full international cooperation and coordination will be required.

Bibliography

Board on Agriculture and Renewable Resources, 1976. *Climate and Food: Climatic Fluctuation and U.S. Agricultural Production*, National Academy of Sciences, Washington, D.C., 212 pp.

Climatic Impact Committee, 1975. *Environmental Impact of Stratospheric Flight: Biological and Climatic Effects of Aircraft Emissions in the Stratosphere*, National Academy of Sciences, Washington, D.C., 348 pp.

Commission on International Relations, 1977. *World Food and Nutrition Study: The Potential Contributions of Research*, National Academy of Sciences, Washington, D.C., 192 pp.

Committee on Atmospheric Sciences, 1971. *The Atmospheric Sciences and Man's Needs: Priorities for the Future*, National Academy of Sciences, Washington, D.C., 88 pp.

Committee on Atmospheric Sciences, 1973. *Weather and Climate Modification: Problems and Progress*, National Academy of Sciences, Washington, D.C., 258 pp.

Committee on Atmospheric Sciences, 1977. *The Atmospheric Sciences: Problems and Applications*, National Academy of Sciences, Washington, D.C., 124 pp.

Committee on Impacts of Stratospheric Change, 1976a. *Halocarbons: Effects on Stratospheric Ozone*, National Academy of Sciences, Washington, D.C., 352 pp.

Committee on Impacts of Stratospheric Change, 1976b. *Halocarbons: Environmental Effects of Chlorofluoromethane Release*, National Academy of Sciences, Washington, D.C., 125 pp.

GARP, 1974, Report of the tenth session of the joint organizing committee, JOC X, World Meteorological Organization, Geneva, 37+ pp.

GARP, 1975. Report of the eleventh session of the joint organizing committee, JOC XI, World Meteorological Organization, Geneva, 51+ pp.

GARP, 1976a. Report of the twelfth session of the joint organizing committee, JOC XII, World Meteorological Organization, Geneva, 28+ pp.

GARP, 1976b. Report of the twelfth session of the joint organizing committee, JOC XII, Annex G, Report of the JOC *ad hoc* working group on the global data base for climate research, World Meteorological Organization, Geneva, 28+ pp.

GARP, 1977. Report of the thirteenth session of the joint organizing committee, JOC XIII, World Meteorological Organization, Geneva, 37+ pp.

GARP Joint Organizing Committee, 1975. *The Physical Basis of Climate and Climate Modelling*, GARP Publications Series No. 16, World Meteorological Organization, Geneva, 265 pp.

Geophysics Research Board, 1977a. *Studies in Geophysics–Climate, Climatic Change, and Water Supply*, National Academy of Sciences, Washington, D.C., 132 pp.

Geophysics Research Board, 1977b. *Studies in Geophysics–Energy and Climate*, National Academy of Sciences, Washington, D.C., 158 pp.

Geophysics Research Board, 1977c. *Studies in Geophysics–The Upper Atmosphere and Magnetosphere*, National Academy of Sciences, Washington, D.C., 168 pp.

U.S. Committee for the Global Atmospheric Research Program, 1975. *Understanding Climatic Change: A Program for Action*, National Academy of Sciences, Washington, D.C., 239 pp.