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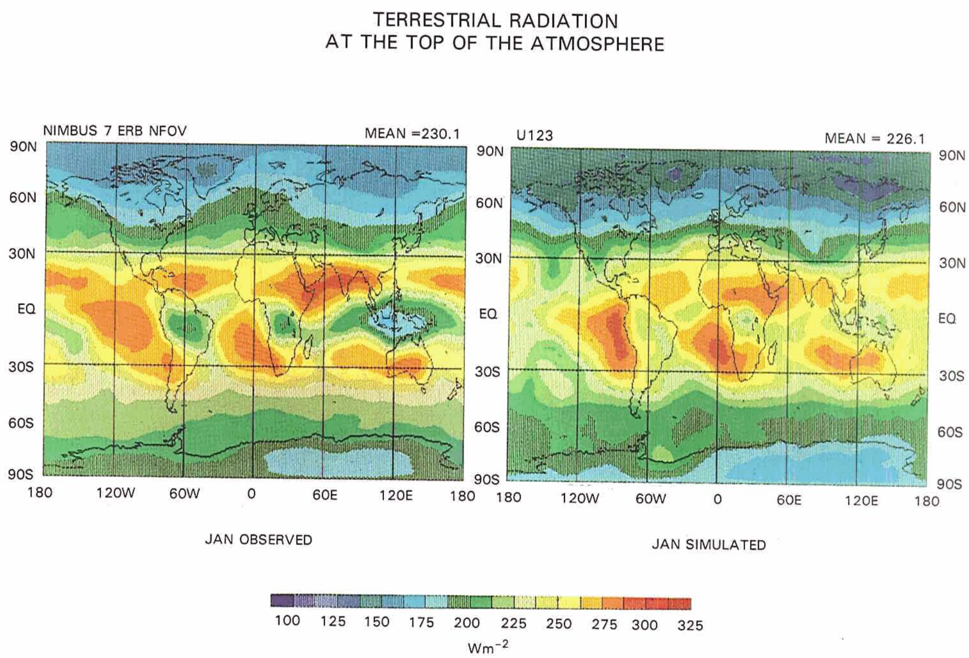

An Element of the NASA Climate Research Program

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Understanding Climate: A Strategy for Climate Modeling and Predictability Research

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PREFACE

The overall goal of the NASA Climate Research Program, a key element of the U.S. National Climate Program, is to develop and exploit a space capability for global observations of climate parameters which will contribute to an improved understanding of those processes which influence climate and its predictability. This requires developing a hierarchy of numerical climate models to guide the design of the global observing system, to aid in understanding the complex physical processes and interactions which control the climate, and to contribute toward the goal of climate predictability. The National Climate Program, in turn, addresses the basic scientific issues outlined by the World Climate Research Program (WCRP).

As described in the Scientific Plan for the WCRP, the main objectives are to determine to what extent climate can be predicted and the extent of man's influence on climate. The primary approach for achieving these objectives is based on the use of physical-mathematical models capable of simulating and, eventually, predicting climate changes over a wide range of space and time scales. Advances in the knowledge of many different physical processes which occur in the atmosphere-ocean-ice system are needed for developing such climate models.

The purpose of this document is to describe the rationale and scope of NASA-sponsored climate modeling and data analysis activities, and to outline a strategy for future research. Clearly, in all aspects of the program, the underlying theme is focused on the use of satellite data. A companion report outlining the strategy for research on Solar and Earth Radiation was issued in 1983.

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EXECUTIVE SUMMARY

The emphasis of the NASA strategy for climate modeling and predictability research is on the utilization of space technology to understand the processes which control the earth's climate system and its sensitivity to natural and man-induced changes and to assess the possibilities for climate prediction on time scales of from about two weeks to several decades. Because the climate is a complex multi-phenomena system, which interacts on a wide range of space and time scales, the diversity of scientific problems addressed requires a hierarchy of models along with the application of modern empirical and statistical techniques which exploit the extensive current and potential future global data sets afforded by space observations. Observing system simulation experiments, exploiting these models and data, will also provide the foundation for the future climate space observing system, e.g., Earth observing system (Eos), NASA 1984; Tropical Rainfall Measuring Mission (TRMM) North, *et al.*, 1985.

Clearly, not all scientific problems fall within NASA's climate research objectives. Thus, in an environment of limited resources, including available research funding, computing capabilities, and scientific manpower, a prioritization must be enforced which responds to the scientific consensus of what is important and yet reflects the realities of the budget. Major topics for NASA climate modeling research are briefly summarized:

Aside from the obvious need for improving models in general, e.g., improved parameterization for sub-grid-scale phenomena and interactions, and in numerical efficiency factors, an expansion in the study of climate processes is vital. Quantitative assessment of relative roles of competing forcing and feedback mechanisms, as well as the myriad of climate system internal fluctuations is essential in analyzing the potential climatic impact of man-induced changes such as the minor constituent composition of the atmosphere, e.g., CO_2, CH_4, $CFCl_3$, CF_2Cl_2, and tropospheric O_3, and in land surface properties. Specific examples of such key processes, outlined in the Scientific Plan for the World Climate Research Program (WMO/TD6) are:

- hydrological processes and fluxes of heat and moisture from the oceans and land surfaces,
- oceanic processes involving the dynamics of the ocean circulation and momentum-energy-water exchange through the ocean-atmosphere interface, and
- radiative processes in the atmosphere including the effects of extended cloudiness, minor gaseous constituents, and particulate matter.

The current NASA thrust is on characterizing the nature of cloud-radiation feedback and on understanding the role of the oceans as a thermal buffer and major source of internal climate variability. Another important program component involves the planetary boundary layer processes, particularly with regard to tropical energetics and latent heat transport to extra-tropical regions. Progress in the latter is dependent on the improvement of coupled ocean-atmosphere models, first with the ocean mixed layer for short-range problems such as the El Nino phenomenon, and subsequently with the deep ocean for studies of long-range climate change.

Equal emphasis should be given to both short-range and long-range climate studies, and the corresponding need for developing improved modeling tools. Short-range (seasonal and interannual) climate fluctuations which have obvious connections to certain extreme anomalies such as the recent El Nino event (1982-1983) and the El Chichon volcanic eruption (1982) must be understood to evaluate existing skill for climate prediction and thus carry a high priority in modeling research. Understanding the long-range (decadal to 50 or more years) climate impact of natural and man-induced changes is viewed to be of similar priority. Indeed, virtually all processes which have a bearing on the long-range prediction problem play some role in the corresponding shorter-range problem and are relevant for current study.

It is apparent that a coherent climate modeling research program that is consistent with NASA objectives must involve a strong data analysis component. Information contained in the global data sets acquired by remote sensing from satellites can provide a unique resource for defining initial state and boundary conditions for model experiments, serve as a factor in model output verification, and provide valuable insight into subtle relationships and teleconnections among climate variables, which can then be explored in detail with the sophisticated numerical models.

In validating numerical climate models, a fundamental test is their ability to reproduce the first- and higher-order statistics of the key climate variables. Further research is thus required on new methodologies for analyzing and mapping the statistical properties of large geophysical parameter data sets obtained both through satellite observations and as the output of climate modeling experiments.

The Experimental Climate Forecast Center (XCFC) at the NASA Goddard Space Flight Center will continue to support the objectives of the National Climate Program through the analysis of historical data and scenarios. Operational type real-time forecasting is specifically excluded from the activities of the Center.

For all climate research activities covered by this plan, specific tasks will be defined through unsolicited proposals submitted to the Office of Space Science and Applications at NASA Headquarters.

I. OVERVIEW: CLIMATE AND CLIMATE MODELING

The climate can be narrowly defined as the statistical properties of the weather, averaged over a period longer than the deterministic limit of predictability for the internal dynamics of the atmosphere, i.e., longer than about two weeks. However, since the climatic state and its variability depend crucially on the oceans, the ice sheets, and the biosphere, it is useful to generalize the definition of climate to include the statistical properties of this larger, composite system, still averaging over a time interval greater than or equal to the deterministic limit of predictability for the atmosphere alone.

To understand how the climate system works and to gain maximum knowledge of future climate variations and trends, a broad range of climate modeling research based on space technology is underway. Practical benefits of improved understanding should include anticipation of many short-term climate effects and foreknowledge of the consequences of anthropogenic climate influence.

A. The Climate System

The study of climate addresses a broad range of questions, including the following:

What is the current state of the climate system? Climatic state variables are incredibly diverse. They include the atmospheric temperature, precipitation, cloudiness, and wind velocity; the sea surface temperature, thermocline depth, and deep ocean currents; sea ice extent, ice sheet thickness, and rate of glacial advance; and the distributions of biomass on land and in the oceans. Both the means and the higher-order spatial and temporal statistics of all these variables define the current state of the climate. Space observations are an essential component of the climate monitoring system because of their global coverage and unique vantage point.

Why is the current climate as observed? To what extent can we explain the current state of the climate system in terms of such external parameters as the solar constant, the geometry of the earth's orbit, the composition of the atmosphere, the distribution of land and sea, and the locations and heights of the mountains? Is the climate system currently in equilibrium?

How has the climate varied in the past? A wide variety of techniques have revealed the history of climatic change, including the occurrence of ice ages and the formation of deserts. Study of this history can provide clues to the mechanisms of climate change, and suggests that the present climate is temporary and somewhat fragile.

Why does climate change occur? Changes in the earth's orbital parameters, fluctuations of solar energy output, continental drift, volcanic activity, and asteroidal impacts have all been proposed as instigators of climate change. The degree to which each of these mechanisms can account for components of the observed climate variability is the subject of intensive research.

How will the climate change in the future, particularly as a result of man's activities? The build-up of atmospheric CO_2, agricultural practices such as the clearing of forests and livestock grazing, and nuclear war are examples of human activities that might lead to significant long-term or short-term climate change. If climate change can be predicted, it may be possible to influence it, or at least to plan for it.

Do the slowly varying components of the climate system make it possible to predict the monthly or seasonal mean weather a season or more in advance? Even modest skill in seasonal forecasts could be of enormous economic importance. Agricultural and energy planning would benefit greatly.

B. Climate Modeling

A climate model is a set of mathematical relations quantitatively representing the physical relationships among the various state variables of the climate system. Climate modeling is essential to answering every one of the questions listed above. Diverse measurements distributed inhomogeneously in time and space become much more useful if they are dynamically interpolated by assimilation into three-dimensional general circulation models (GCMs). In this way, the models help to describe the observed climate. High-resolution GCMs provide remarkably accurate simulations of the observed climate, when realistic boundary conditions are specified. Analysis of the model results and tests of the sensitivity of the results to variations in the observed parameters can provide insights into the mechanisms that maintain the current climate. Simulations of past climates can fill the gaps in paleoclimate data sets, at the same time suggesting explanations for past climate changes. The models can also be used in an attempt to predict climate variations that will accompany future increases in atmospheric CO_2 content, or changes in land-use practices. Finally, there is a growing body of evidence that short-term climate fluctuations, such as those associated with the El Nino/Southern Oscillation events, can be predicted months or more in advance. This possible application of the models to short-term climate prediction is very exciting, but is still very much in the experimental stage.

There are many kinds of climate models, simply because no single model can address the full range of questions. For some problems, the most detailed, realistic model possible is needed. For others, a detailed model is unnecessary and/or impractical. The need for a hierarchy of models will not go away when more powerful computers become available. As an example, consider a researcher using a coupled troposphere/upper ocean/sea ice/land surface model of medium resolution to conduct climate simulations of ten-year duration. Suppose that overnight the computing resources available are increased dramatically. The researcher can make use of this increased computing power in a variety of ways: by increasing the resolution of the model to improve the quality of the simulation; by enlarging the domain of the model to include the deep oceans and the stratosphere; by extending the duration of the simulations to a century or more; by performing a larger number of simulations; or by some combination of these. The point is that *all* of these options make sense. Each option calls for a different model development strategy. For this reason, future increases in computing power will lead to an even greater diversity of models.

We can distinguish four types of climate models that are in current use. In order of increasing complexity, they are:

Energy-balance models. These models are based on highly simplified expressions of the conservation of energy for the earth-atmosphere system. Atmospheric motions are included only parametrically. Because of their extreme simplicity, these models cost practically nothing to run, and their results are relatively easy to understand. However, they necessarily include a high degree of empiricism, and they are incapable of representing more than the simplest statistics of a few climate state variables. They can be used to simulate very long-term climate change, e.g., in response to changes in the earth's orbital parameters.

Radiative-convective models. In their most advanced form, these are one-dimensional versions of the physical parameterizations used in general circulation models. They are economical, but they do not include the effects of large-scale motions. They can be used to study the response of the vertical structure of the atmosphere to changes in radiative forcing or trace-gas composition, and also to evaluate new physical parameterizations intended for later use in GCMs.

Low-resolution atmospheric general circulation models. These models achieve relatively high computational efficiency at the expense of crude resolution of individual synoptic eddies. They can be routinely used in runs of several decades duration, making them well-suited for studies of interannual variability.

High-resolution atmospheric general circulation models. These models are better able to resolve synoptic eddies, but, because they are computationally expensive, they are limited to runs of only a few years duration. They show the limit of how well we can simulate climate, but at considerable expense.

C. Impact of Satellite Data

The study of climate and climate processes on all time and space scales requires vast amounts of conventional and satellite observational data for a variety of reasons, i.e., including (1) direct input for initialization and/or updating of models, (2) developing parameterizations for model physical processes, (3) testing the validity of models, and (4) diagnosing climate signals not readily apparent from conventional data alone.

Except perhaps for a few specific regions where observational instrumentation is reasonably dense, there has always been a paucity of data to document global climate and to detect climate change, especially over the vast ocean areas (70% of the globe). But in more recent times we are beginning to see some light at the end of the tunnel as we learn how to use remote observations, from satellites, of the earth-atmosphere system.

A number of satellite data sets have been developed in the last 10 years from both research and operational satellites that are applicable to climate models and statistical studies related to climate diagnostics and detection of climate change, e.g., earth radiation budget, temperature and moisture fields, sea surface temperature, clouds, sea ice, snow cover, ice sheets, aerosols, ozone, crude estimates of rainfall and soil moisture, and some information on winds through observing cloud movement and sea surface roughness.

These data have already been used extensively to test model capabilities and to improve them. Global models (GCMs) are increasingly making use of satellite data in various ways to prescribe boundary conditions and/or to provide initialization variables. In some cases, climatology is used for these purposes, but many modern climatologies have been extensively enhanced with satellite data.

It has always been a problem to evaluate cloudiness parameterization in GCMs because of insufficient data on global cloudiness. Earlier comparisons had to rely on ground observations and ship and aircraft reports. Now, however, we are developing sophisticated cloud data sets through the International Satellite Cloud Climatology Project (ISCCP) (1983-1988) to provide the necessary comparative data to test model validity.

Only recently have we been able to make significant progress with sea-ice models, which are so important to understanding atmosphere — sea-ice interactions and their effects on climate. Long-term satellite sea-ice atlases have just begun to be developed with satellite microwave and visible and infrared radiometer observations. Many more years of satellite data will be needed, however, to accurately model interannual and long-term sea-ice effects.

In modeling land processes and their effects on climate, estimates of soil moisture, vegetation, snow cover related to albedo changes, etc., from satellite observations have been invaluable because large-area data of sufficient quality are not available in any other way.

One of the most critical issues is the availability of reliable rainfall data for climate modeling validation and diagnostic studies especially as the models become more sophisticated. This is because the global atmospheric heat engine is primarily driven by the localized release of latent heat during the ascent of warm, moisture-laden air in the equatorial rain belts. Regional and temporal shifts in tropical rainfall patterns produce complex responses in atmospheric planetary waves with effects propagating well into the mid latitudes. The recent El Nino episode and its impact on worldwide weather are an extreme example of the phenomena associated with tropical rainfall variations. Less intense but more frequent monthly and seasonal fluctuations, also related to rainfall, are evident as well. Unfortunately, the surface observational network is extremely sparse in the important, largely oceanic, equatorial zone with many critical areas beyond the range of surface radar coverage even if maximum advantage were to be taken of possible locations for deployment. Now, however, the sampling problem and observational techniques to obtain the precision rainfall statistics for the required time periods are sufficiently well understood that it is time to make a concerted effort to acquire these critical measurements from space.

For verifying model capabilities, a fundamental test is the model's ability to reproduce the first-order statistics of the atmosphere such as the seasonal cycle. The representation of the seasonal cycle is most conveniently done by displaying the various time harmonics of the cycle. For easy comparisons to model output, for example, terrestrial radiation data from the Nimbus-7 satellite and temperature fields from the NOAA operational satellites have been analyzed in a similar form.

A recent and more direct use of satellite data was the ability to detect a significant connection between tropical Pacific atmospheric/ocean anomalies and the North American (PNA) weather pattern with only 7 years of data (earth radiation budget) as opposed to 30 years of conventional meteorological data used earlier to get a glimpse of this phenomenon. This analysis of the satellite data led to the development of a stochastic model which has some predictive skill relative to tropical and extra-tropical weather and climate teleconnections.

Finally, the Experimental Climate Forecast Center (XCFC) that the NASA Goddard Space Flight Center has established at the request of the National Climate Program Office, will conduct research that depends heavily on past satellite data for model inputs and for their validation.

II. STATE OF THE ART OF CLIMATE MODELING

A. Introduction

NASA climate modeling research is carried out in the context of the broader National Climate Program. The objective of the NASA research is to optimize the development and utility of global climate observations from space. Achievement of this specific objective requires an in-house climate research and modeling capability, which is contributing to advancement of the state of the art.

Substantial progress has been obtained in the past 25 years in our understanding and modeling capabilities for both short- and long-range global climate. The goal of reliable forecasts on monthly, seasonal, and interannual time scales is recognized to depend substantially on both atmospheric dynamics and slowly changing boundary conditions of the atmosphere, e.g., ocean temperatures, land surface conditions. Improvements in our ability to simulate the atmosphere, e.g., numerical techniques and treatment of convection and clouds, and the atmosphere's changing boundary conditions, e.g., ground moisture and sea surface temperature, are needed in order that we can assess short-range climate variability and its potential predictability, and thus assess the utility of specific global measurements for achieving understanding and predictability of short-range regional climate.

Long-range global climate trends are recognized to depend on perturbations of the planetary radiation balance with space and climate feedback processes, which amplify or diminish the response to changed climate forcing, as well as internal fluctuations of the climate system. Quantitative assessments of the roles of different climate forcings, feedback processes, and internal climate system fluctuations are needed in order that we can assess the potential climate impact of man-made perturbations such as changes of atmospheric CO_2 and other trace gases (''greenhouse effect'') and land surface properties. Principal among the parts of the climate system which have been identified as requiring improved understanding and modeling are the role of clouds as a climate feedback mechanism and the role of the ocean as a thermal buffer and as a source of natural or internal climate variability.

Despite the progress which has been achieved in understanding and modeling of climate, it is essential that a critical view of modeling capabilities be maintained. Even the most comprehensive global climate models (GCMs) greatly oversimplify or misrepresent key climate processes. Although GCMs have many disposable parameters, current atmospheric models have major deficiencies in their ability to simulate basic climate processes, such as transports by atmospheric eddies, long waves, storm tracks, and regional climate patterns; moreover, realistic coupled ocean/atmosphere models remain a goal for the future. Thus it is crucial that a vigorous research effort directed toward understanding the fundamental physics of the climate system be maintained in parallel with improvement of climate models.

Climate models generally are tuned to represent today's climate, but the desired applications concern climate fluctuations from the mean. The ability of current models to represent second-order climate statistics is very uncertain. It is thus particularly important to test climate models against observations in cases of fluctuations of climate or climate forcing. Examples of such test cases include El Ninos, volcanic eruptions such as El Chichon, paleoclimate fluctuations, and even application of climate models to other planets. In many of these cases satellite observations can provide the necessary global observations of climate forcing and/or climate response.

In the first two sections below we briefly describe the status of our understanding and modeling abilities for short- and long-range global climate variations. Emphasis is on areas where lack of understanding is thought to have greatest potential significance. The state of the art in several of these key areas (clouds, oceans, ice, land surface processes) is discussed in more detail later. The physical processes in these areas are significant for both short-range and long-range climate, though the role and relevant modeling needs may differ greatly. For example, the ocean surface temperature influences short-range climate; the widespread influences of surface temperature anomalies associated with El Nino phenomena suggest that it would be valuable to have a modeling capability for the upper layers of the low-latitude ocean. On the other hand, long-range climate depends crucially on the exchange between the mixed layer and the deeper ocean as well as on the potential effects of surface climate trends on poleward transport of heat in the ocean; this suggests the need for modeling the entire ocean for long-range climate studies.

References in this section are cited in only a highly selective fashion. Some relevant review papers in which additional references can be found are Schneider and Dickinson (1974), Ramanathan and Coakley (1978), North *et al.* (1981), Gates (1979), and Dickinson (1982).

B. Global Climate Models

For our purposes here, climate is taken as all atmospheric (and oceanic) phenomena on time scales longer than about two weeks. This definition is useful, not because there is a clear separation of phenomenology at this interval, but because it is the theoretical limit of deterministic prediction of individual events in the atmosphere. The distinction between weather and climate is made on the basis of what we can hope to predict, rather than on the physics that is to be studied. Of course as the time scale considered increases, the physics does alter, with slower processes becoming more important.

We divide the total range of climate scales into two parts. Short-range climate is taken as extending from monthly through seasonal and interannual climate variations. Long-range climate is taken as extending from decadal to all longer time scales.

1. Short Range Climate

Although the theoretical limit on weather prediction precludes us from predicting a definite time history of events, it leaves open the possibility of predicting time and space means beyond the two-week interval. Thus while we will never be able to make the prediction that a storm will be over a certain area a month from now, we may be able to say that, on the average, next month will have more storms, or next season will be unusually cold or dry over some suitably large area.

At the shorter end of the range, modeling focuses on establishing predictability of means. The objective is to extract skill from the *low-frequency* end of the atmosphere's variability. The strategy is a direct extension of numerical weather prediction, but seeks only to say something of statistics over the extended range. The models used are the large and detailed weather prediction models. Work in this area is discussed further in Chapter IV.

At the longer end of the short-range climate time scales, i.e., interseasonal and interannual periods, internal low-frequency atmospheric variability can explain only a diminishing part of the observed variance, with the slow processes at the land surface and in the oceans contributing to the departure of the atmospheric state from its long-term statistical steady state. If, for a moment, we limit our consideration to the atmosphere and view the state of the land surface (its vegetation and soil moisture) and the ocean (its surface temperature) as fixed or very slowly varying on the time scales of interest, atmospheric predictability consists of being able to distinguish the long-term effects on the atmosphere of departures from their normals of the states of the land and ocean surface. This is the approach taken in sensitivity studies of the atmospheric response to, say, anomalies in ground wetness or sea surface temperature. Lorenz called this prediction "of the second kind," dependent only on external parameters (boundary conditions); predictions dependent on the initial atmospheric state he termed "of the first kind." For a given system, climate variations of the first kind, such as we discussed for the atmosphere at short range, tend to impede predictability of the second kind. That is, a natural tendency of the system to remain for long periods far from its statistical steady state, i.e., to have a long 'memory' of its earlier atmospheric state, would make it hard to tell whether a particular departure was internally forced or due to a change of boundary conditions. There is reason to believe both internally and externally forced variability are important on the seasonal to interannual time scale.

Most of the work in this area of predictions of the second kind has been in the study of the atmospheric response to sea surface temperature anomalies. Recently, attention has focused on the tropical anomalies associated with El Nino events, with a number of modeling groups attempting simulations of the atmospheric response. Unlike the case of mid-latitude anomalies, for which no significant atmospheric response has been established, these studies show the tropical atmosphere to be quite sensitive to tropical sea surface temperatures, and the weight of the evidence, both modeling and observational, is rapidly growing for the occurrence of a significant mid-latitude response to tropical sea-surface temperature anomalies.

Sensitivity studies will no doubt continue to play an important role in the study of seasonal to interannual predictability. But the realization that successful predictions of the second kind can be made with both ocean and atmospheric models for El Nino events has led to serious consideration of predictions based on coupled ocean-atmospheric models. Also, with such an expanded model, predictions of the first kind would include predictions of the slowly varying components of the system. So far these have been mostly limited to simple and very idealized models, but as understanding of the processes governing the coupled dynamics of the two systems improves, more detailed ocean and atmosphere general circulation models will be used.

2. Long Range Climate

Modeling can play a major role in improving our understanding of long-range climate and in defining global observational requirements. In this section we briefly discuss the status of modeling capabilities, focusing on needed model improvements. The use of models in analysis of climate data is discussed in a later section.

In recent decades, our understanding of the global planetary radiation budget has improved greatly, as has our ability to compute accurately the strength of specified radiative forcings of the climate system. However, this does not allow us to understand how the climate will change, even if we have accurate measurements and projections of changing climate forcings. The primary reason is that there are large uncertainties in the climate feedback processes which occur in response to any climate change. The feedbacks include not only processes which modify the global planetary radiation budget, but also effects on internal climate dynamics such as the atmospheric general circulation and effects on ocean currents and vertical mixing. In some cases even the sense of the feedback is uncertain. Improved models, in conjunction with observations and data analysis, are needed to improve this situation.

Simplified global climate models (such as 1-D radiative/convective models, energy balance models, zonally symmetric circulation models) and special process models (such as cloud models, thermocline ventilation models, evapotranspiration models) are an essential part of climate analysis. By isolating or simplifying climate processes, these models make it possible to develop a better understanding of important physical mechanisms, analyze specific data, and develop parameterizations for more comprehensive models. It is inappropriate to rigidly specify what special models are needed, since they should be developed, tested, and modified as needs change. However, it is possible to point out examples of special models currently of value and areas where development is needed.

1-D radiative/convective models have been in use for 20 years as a tool for estimating global mean climate (temperature) sensitivity. More recently they have been used to analyze the global mean contributions of different radiative feedback processes in 3-D climate experiments; an example is shown in Fig. 1 for analysis of the contributions to the global mean warming in 3-D doubled-CO_2 climate experiments. Although these initial studies point toward the importance of several specific physical processes, more analysis is needed. It would be useful, for example, to perform 1-D analyses on a regional or latitudinal basis, with horizontal transports of energy which could be obtained from the 3-D model (or otherwise explicitly incorporated).

2-D models which compute (in some parameterized way) dynamical energy fluxes, provide another useful tool for examining climate processes and climate sensitivity. A recent example is the model of Peng *et al.* (1982), which has been used by Chou *et al.* (1982) to study feedback mechanisms in the CO_2 problem. It would be useful to make comprehensive comparisons of the processes occurring in 1-D, 2-D, and 3-D models for climate perturbations such as increased CO_2.

Another useful simplified approach is an energy balance model which includes two horizontal dimensions and the seasonal cycle but only one vertical level (North *et al.*, 1983a). Studies with this model show explicitly how the land-sea geography modulates the annual march of temperature, and how alterations of paleogeography or the earth's orbital geometry might have caused large shifts in the equilibrium climate (North and Crowley, 1984). The model is primarily used as a tool for pilot studies that would be too expensive or confusing to run at present on a full GCM. Examples of applications include the transient climate response patterns to various CO_2-increase scenarios (North *et al.*, 1984) and to solar constant variations (North *et al.*, 1983b).

Individual climate process models are particularly important for improving our understanding of the overall climate system. An example is the representation of cloud processes, which is perhaps the greatest source of uncertainty in our understanding of the equilibrium sensitivity of the climate system to a change of global forcing. Development of more realistic models for cloud formation, comparisons with observational data, and construction of parameterizations for 3-D climate models should have high priority with the advent of global cloud data sets from the International Satellite Cloud Climatology Project (ISCCP). Present ideas about cloud modeling needs are discussed in more detail in a section below.

Some other processes which are thought to be of particular importance to long-range climate include the following. Ocean uptake of heat and the sensitivity of this process to changes of surface climate are a major source of uncertainty in attempts to project future climate on the 10-100-year time scale. Ice (sea ice and ice sheets) sensitivity to climate change and the role of ice as a climate feedback mechanism remain uncertain. Land surface processes, particularly ground hydrology and its relation to vegetative cover is another area requiring improved understanding and modeling. These few examples, which are not exhaustive, are discussed in more detail in Section IIC.

Full three-dimensional modeling is an essential part of climate analysis, given the complexity of the climate system and the need for an understanding of regional as well as global climate. State-of-the-art 3-D models are important for diagnostic studies and can reproduce the observed atmospheric general circulation reasonably well, but the realism of the models is still far short of what is needed for climate applications. The following discussion outlines principal modeling capabilities

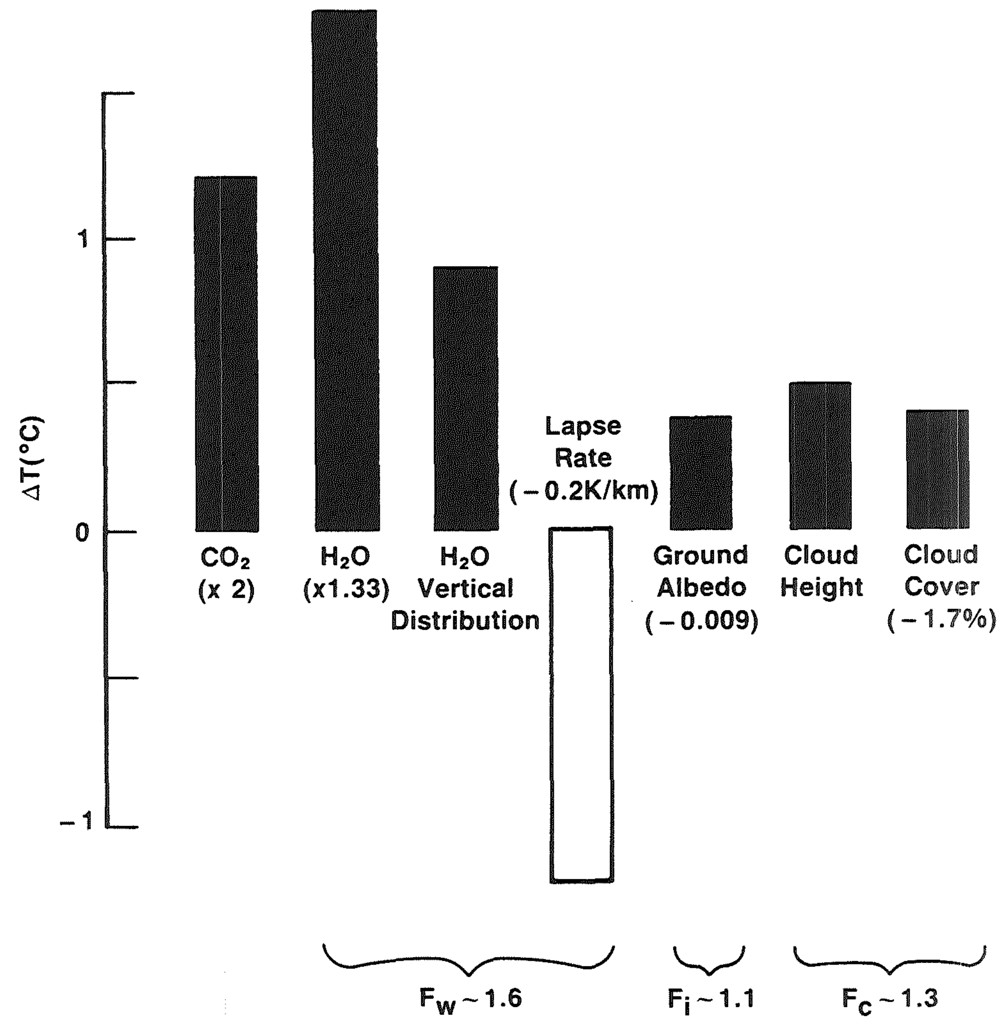

Figure 1. Contributions to the global mean temperature rise in the 3-D doubled-CO_2 experiment of Hansen *et al.* (1984) as estimated by inserting the changes obtained in the 3-D experiment into a 1-D radiative/convective model. F_W, F_i, and F_C are the water vapor, ice/snow, and cloud feedback factors, defined as the factor by which the temperature response is increased by a given feedback process operating by itself.

that are desired for climate analysis and prediction purposes, and identifies some of the areas in which model improvements are feasible during the next several years.

The first quantity studied with climate models is the temperature and its sensitivity to variations of climate forcings. Although the models can produce realistic values for today's climate, in many ways they are 'tuned' for this condition. When a given climate forcing or perturbation (such as increased CO_2) is applied to the models, they show a broad range of climate sensitivities. Even if the set of models is restricted to the 3-D global models, which are the most detailed and presumably the most realistic, the computed climate sensitivities range over a factor of two: Manabe and Stouffer (1980) obtain a 2 °C global mean warming for doubled CO_2 (as estimated from an experiment in which CO_2 was quadrupled), while Hansen *et al.* (1984) obtain a 4 °C warming. This range occurs despite the fact that the models probably have many common deficiencies.

The range of the inferred climate (temperature) sensitivities must result primarily from differences in the climate feedback processes, such as those illustrated in Fig. 1, since the basic radiative forcing can be computed accurately. It is realistic to expect that our knowledge of these feedbacks can be improved in the next several years as the modeling capabilities for these processes improve, and as observations needed for testing the models become available. However, the difficulty in obtaining a good understanding should not be understated. For example, note that the cloud feedback in Fig. 1 is computed to be one of the most substantial feedbacks (for this model), even though it involves only moderate changes of cloud cover and cloud height. Research needed in some of the key areas, such as clouds and convection physics, sea ice processes, ground hydrology, and vegetation effects, is discussed more specifically below.

The regional distribution of climate sensitivity must be understood before the practical implication of long-range climate trends can be evaluated. Models presently in use fall far short of being adequate for this purpose (see, for example, the review paper by Schlesinger, 1984). Improvements in the areas mentioned above with regard to global climate sensitivity, if attained, may also go a long way toward improving abilities to study regional climate variations. However, regional climate sensitivity is expected to depend also on the sensitivity of the ocean to any climate change at the ocean surface. It is expected to require many years to develop the required ocean modeling capability.

Changes in precipitation distributions may have greater practical importance than changes in temperature, yet they are even more difficult to model. Sensitivity studies have shown that the computed precipitation patterns strongly depend on the representation of evapotranspiration processes, including the influence of vegetation (Shukla and Mintz, 1982; Rind, 1984). However, it is also crucial to represent realistically other physical processes such as convection and to use accurate finite difference formulations for the water vapor distribution and other prognostic variables. Attainment of the objectives of 3-D climate modeling will require improvements across the broad range of model components, as well as testing of model capabilities against modern satellite and paleoclimate data.

C. Key Climate Processes

1. Clouds

Prediction of the distribution of cloudiness and its interactions with other components of the climate system is one of the most important goals and, at the same time, one of the most difficult tasks in climate modeling. Changes in cloudiness critically affect the global energy budget in two competing ways: by modifying the planetary albedo and the emitted infrared radiation. For low clouds the albedo effect dominates (Manabe and Wetherald, 1976), i.e., increasing the amount of low clouds, other things being equal, leads to cooling at the surface. However, if changes in cloud height are associated with changes in cloud amount, the results can be significantly different (Schneider, 1972). Empirical studies based on the observed temporal and spatial variability of cloudiness and of radiative fluxes at the top of the atmosphere (Cess, 1967; Ohring and Clapp, 1980; Hartmann and Short, 1980; Cess *et al.*, 1982) are inconclusive, giving results that vary from a dominance of the albedo effect to a near-perfect balance between long- and short-wave changes. The safest conclusion from these studies is that many details of the cloudiness distribution must be more accurately modeled to conclusively assess the influence of clouds on the variability of climate.

GCMs typically predict two "kinds" of clouds: convective clouds and large-scale clouds. Convective clouds are those for which buoyancy-driven subgrid-scale motions play a dominant role. The parameterization of convective clouds must take into account both the large-scale static stability and the large-scale relative humidity. In all existing convection parameterizations, the intensity of convection depends in some way on the rate at which the column is being destabilized by radiation and by the large-scale circulation. In this way the field of convection and the cloudiness inferred from it depend on both the thermodynamic state—the static stability and the relative humidity—and its large-scale tendency.

The relationship between convective heating and convective cloudiness is not obvious. Although the results of the convection parameterization should imply something about the fractional cloud cover, active deep convection typically accounts for only a few percent of the observed fractional cloudiness (in fact, the smallness of the region of active convection is an explicit assumption in some parameterizations); inactive cloud debris and cirrus shields account for most of the observed cloudiness. Some memory of the history of convection and some statement about the life cycle of convective clouds thus seem to be necessary ingredients of a cloud parameterization. As far as we know, however, no scheme currently used in a GCM takes such effects explicitly into account. However, since the effects of convection tend to moisten the upper troposphere, cirrus shields and coverage by shallow inactive clouds are to some extent included in the "large-scale" cloudiness parameterization.

Non-penetrative convective clouds and convection not arising in the planetary boundary layer (PBL) have received special attention in some models. Both are included in a crude way under moist convective adjustment. Ramanathan and Dickinson (1981) proposed an empirical parameterization of non-penetrative convective clouds, based on the idea of Lilly (1968), Deardorff (1976), and Randall (1980b). A more detailed parameterization of these clouds is included as part of the PBL parameterization in the University of California, Los Angeles (UCLA) model (Suarez *et al.*, 1983).

Large-scale cloudiness parameterizations are quite crude. The fractional cloud cover is generally diagnosed using the relative humidity field alone, e.g., Smagorinsky (1960). The simplest schemes assume overcast conditions when the model grid box becomes saturated, or make cloudiness some simple function of relative humidity.

A very different approach to modeling large-scale, non-convective clouds has been proposed by Sundqvist (1978), who introduces a prognostic equation for cloud water, and writes source and sink terms by making assumptions for condensation, evaporation, and precipitation over a fraction of the grid area. Fractional cloudiness schemes based on knowledge of the second-order statistics of temperature and total water mixing ratio have also been proposed (Sommeria and Deardorff, 1977; Mellor, 1977; Hansen *et al.*, 1983). However, neither prognostic schemes nor statistical condensation methods have yet been widely used in GCMs; the former because of the difficulty in formulating source and sink terms for liquid water with an accuracy that would justify retaining separate storage and advection terms for water vapor and total water, the latter for a lack of useful diagnostic relations for the higher statistics (prognostic equations for the higher statistics are beyond our current reach both theoretically and computationally).

The parameterizations discussed thus far depend only on thermodynamic quantities and their large-scale tendencies. Situations in which a more direct dependence on the large-scale motion exists are probably common. Examples are deep convection in the presence of vertical wind shear (Moncrieff, 1978; Thorpe *et al.*, 1982; Emanuel, 1983a,b), and the effects of shear on the maintenance of stratocumulus layers (Brost *et al.*, 1982) and on the organization of cellular shallow cumuli.

The evaluation of cloudiness parameterizations in GCMs must deal with two major difficulties: establishing a proper comparison with observations, and tracing any observed deficiencies to their cause in the model. For global comparisons, we must rely on satellite observations. These give us radiances at the top of the atmosphere, which must be inverted to obtain cloud fraction, cloud-top height, emissivity, and albedo. In principle, we could bypass this inversion process and compare modeled and observed radiative fluxes directly. However, this would introduce errors due to the GCM's relatively simple radiative transfer calculations, including the assumptions made for the radiative properties of the clouds. On the other hand, if the inverted fields were used, we would be looking at cloudiness through the radiative transfer calculation used in the inversion whose representation of cloud parameters might be quite different from the GCM's. Care must be taken to understand the relation between the radiative models underlying both GCM output and observational analysis.

2. Oceans

Any assessment of the state of the art in ocean modeling must begin with a definition of the problems of interest, since the ocean interacts with the atmosphere on an extremely wide range of time scales. For this discussion, it is useful to consider two climate problems defined by the World Climate Research Program (WCRP): interannual variability and long-term energetic balances.

The goals of the WCRP are formulated in terms of three specific objectives or streams of climate research, each corresponding to a different time scale. The first stream aims at establishing the physical basis for the prediction of weather anomalies on scales of one to two months. This requires observing the initial value of the ocean surface temperature and sea ice fields, and making progress in the ability to predict the relatively rapid changes of the land surface boundary conditions, e.g., the amount of stored soil water and the rate of evaporation. Further improvements are also needed in the prediction of precipitation and extended clouds, and in the formulation of radiative transfer in the presence of such clouds.

The second stream aims at predicting the variations of the global climate over periods up to several years. These are particularly evident in the tropical regions. The largest contribution to the variations of the global atmosphere which may be predictable on interannual time scales is now seen to be the influence of the oceans and, especially, the tropical oceans in which large-scale circulation and temperature anomalies can be forced by remote atmospheric events and propagate along the equator. The scientific strategy for stream 2 is based on studying and, eventually, modeling the coupled atmosphere-ocean system. Other physical factors, e.g., interannual variations of sea ice, need to be taken into consideration.

The third stream aims at characterizing variations of climate over periods of several decades and assessing the potential response of climate to either natural or man-made influences, such as the increase in the atmospheric concentration of carbon dioxide. The global ocean is a key element in the response of the climate system on such time scales. A major oceanographic program is planned to observe the world ocean circulation and to model the coupled global atmosphere and ocean system.

Regarding interannual variability (Stream 2), the importance of tropical sea surface temperature (SST) and the coupling between the tropical oceans and global climate has been pointed out. Recent work has examined the response of the equatorial ocean to variations in the wind stress, and hindcasts of past events in the Atlantic and Pacific have been carried out. Many models have been constructed which simulate the surface height. These models as in Busalacchi and O'Brien (1981) and Busalacchi and Cane (1985) have captured much of the variability in the sea level records on interannual scales. However, it is much more difficult to model accurately the variations that are of vital interest to the atmosphere, i.e., the sea surface temperature (SST).

Models do exist which attempt to explicitly calculate the variations in surface temperature (Schopf and Cane, 1983; Philander and Pacanowski, 1981). The SST is influenced on these time scales by the variations in the surface currents, upwelling, surface heating, and subsurface flow (the equatorial undercurrent). Success in simulating the SST therefore hinges on a successful simulation of the current field and the surface heating and wind stress.

Perhaps the most apparent success in such simulation has been made by Philander (1984). The model he used is a high-resolution version of the model developed by Bryan (1969) as enhanced by Semtner (1974). The essential change is its extremely high vertical resolution and the parameterization of turbulence using Richardson-number-dependent mixing. The model was forced with winds as estimated for the 1982-3 El Nino event in the Pacific. It gave very realistic simulations of the currents and thermal field in the upper ocean, and was verified against several in situ measurements.

This success was essentially limited by the problem of initialization and the specification of the forcing fields. It appears that the discrepancies between model and observations lie within the differences that would be attributable to the uncertainty in the atmospheric state.

Regarding long-term energetic balances (Stream 3), there is a more difficult problem, for the ocean's role in the global energetics is global and involves the deep ocean in a fundamental way. Here the problem is one of obtaining enough information on the ocean itself to be able to verify and improve model parameterizations and behavior. One interesting new observation technique, which is being used, is the mapping of transient radioactive tracers through the ocean. This allows one to determine the age of the water (time since last at the surface) — a quantity which may be simulated in the circulation models.

The models used for these problems are basically the Bryan (1969) and Semtner (1974) circulation models. Their usefulness is limited by computing resources. Either the global ocean can be modeled with limited resolution (which suppresses features like the Gulf Stream and narrow equatorial cooling) or a single basin can be modeled with high resolution. With current computing resources, ocean circulation studies pertinent to Stream 3 will be fairly idealized.

Coupled ocean and atmosphere. Implicit in the separate discussions above about the roles of the ocean and atmosphere in the climate problem and the strategies being pursued with the two systems for climate modeling, is the notion that the determination of the climate state and its variability depend crucially on ocean-atmosphere interactions. Again it is useful to distinguish between short (interannual) and long time scales (essentially the Stream 2/Stream 3 problems in ocean modeling).

In the interannual climate studies, research is directed primarily at identifying modes of variability inherent in the coupled system. The El Nino/Southern Oscillation phenomenon has received by the far the greatest attention, since there are now good theoretical and observational indications that interactions between the two systems play a key role. Since the time scales involved are relatively short, only the upper layers of the ocean come into play in the Stream 2 problems. Furthermore, the oceanic phenomenon, or at least that believed most important to the atmosphere's behavior, is confined to the tropics. Thus it may be possible to achieve a great deal with modeling which is restricted to the upper, tropical ocean and the global atmosphere over time scales of at most a few years. This allows the use of fairly detailed representations of physical processes in the two systems.

In the long-range climate studies, the goal is to include the effects of the ocean's circulation on the maintenance of the long-term climate equilibrium and on the transient climate trends during the next several decades. Models that accomplish this could be used to study climatic sensitivity to changes in external parameters, such as atmospheric carbon dioxide content. Here, however, the whole of the ocean must be considered and the difficulties discussed above for ocean modeling in Stream 3 severely restrict the potential for detailed modeling of ocean dynamics based on the fundamental equations. At the present state of computing resources, this means that the ocean circulation studies in regard to Stream 3 will be more ad hoc in nature.

3. Ice

Sea ice. Prediction of the distribution of sea ice and its interactions with the oceans and atmosphere is crucial for the proper simulation of detailed climatic conditions in the polar regions. Sea ice is a vital component in the climate system and is both influenced by and influences the oceans and atmosphere. For instance, it serves as a strong insulator, restricting exchanges of heat, mass, and momentum between ocean and atmosphere; it lessens the amount of solar radiation absorbed at the earth's surface, due to its very high albedo relative to that of open ocean; and its formation often results in a deepening of the oceanic mixed layer, sometimes leading to bottom water formation, because of the salt rejection which occurs as the water freezes. Conversely, its motions are significantly influenced by atmospheric winds and ocean currents, and its formation and melt are significantly influenced by atmospheric and oceanic temperatures and oceanic salinity.

Sea ice models typically predict ice thickness and percent areal coverage of ice, i.e., ice 'concentration', doing so with a spatial resolution of about 200 km and a temporal resolution of about one day. The calculations include two major parts: ice thermodynamics, based on energy balances, and ice dynamics, based on a momentum balance. The major energy fluxes at the top surface of the ice (or the snow if there is a snow layer covering the ice) include the sensible and latent heat fluxes between the ice and atmosphere, incoming solar radiation, incoming longwave radiation from the atmosphere, outgoing longwave radiation from the ice, the conductive flux through the ice, and any flux resulting from surface ice melt. At the bottom of the ice, the three major fluxes are the conductive flux through the ice, the oceanic heat flux, and the flux from bottom ablation or accretion. The calculation of ice movements (or ice 'dynamics') is based on Newton's second law of motion, incorporating the major stresses acting on the ice. There appear to be five major stresses: the air stress from above the ice, the water stress from below the ice, the Coriolis force from the rotational motion of the earth, the dynamic topography from the tilt of the sea surface, and the internal ice stresses from the collisions of ice floes.

Several large-scale sea ice models capable of being used in climate simulations have been developed. The models of Washington *et al.*, (1976) and Semtner (1976) are purely thermodynamic models, simulating large-scale features of the ice cover though not incorporating any ice dynamics. The model of Parkinson and Washington (1979) extends the thermodynamic model of Washington *et al.*, to include ice dynamics plus a more detailed lead parameterization. The model of Hibler (1979) also includes both ice thermodynamics and ice dynamics, and increases the sophistication of the treatment of internal ice stresses. Even more detailed are the models developed in connection with the Arctic Ice Dynamics Joint Experiment (AIDJEX), e.g., Pritchard *et al.*, (1976); Coon *et al.*, (1976); Coon (1980), but these were developed for smaller regions and are generally not considered computationally efficient enough for inclusion in large-scale climate simulations. By contrast, the Washington *et al.*, Parkinson and Washington, and Hibler models have each been used in several large-scale sea ice studies over the past several years, e.g., Parkinson and Kellogg (1979); Hibler and Walsh (1982); Hibler and Ackley (1983); Parkinson (1983); Parkinson and Bindschadler (1984), and are each adaptable for coupled climate simulations. Most notably, the Hibler model has been used in coupled ocean/ice simulations (Hibler and Bryan, 1984).

Although there remains important work to be done on improving sea ice models themselves, such as further consideration of the proper constitutive law and its numerical formulation, an equally important need at the moment is the improved incorporation of sea ice into coupled models. This includes ice/ocean coupling, ice/atmosphere coupling, and ocean/ice/atmosphere coupling. Coupled models should then be used to address such issues as the impact of ice formation on oceanic mixed-layer deepening and bottom water formation, the impact of large polynyas (or open water areas) on atmospheric circulation, and the impact on both the atmosphere and oceans of the ice as an insulator. In addition there is the need to check model outputs versus observations. This necessitates continued work on compiling sea ice (and other) data sets for comparison, continued efforts to simulate ice conditions in different years, and continued examination of the issue of proper comparison methods.

Ice sheets. The importance of major ice sheets in the global climate is rapidly becoming recognized. No longer are the ice sheets seen solely as a passive reservoir of the earth's water supply. In either hemisphere, the ice sheets and their connected ice shelves have experienced variations in volume and extent which far exceed the seasonal variations of sea ice. These variations must have affected weather patterns, ocean currents, and, by changing sea level, the entire global climate. However, a major issue yet unresolved is the time scales of these large variations of the ice sheets. Response times for Greenland and Antarctica are usually quoted as thousands to tens of thousands of years, yet data on sea level suggest the possibility of more rapid changes in ice volume (Vail *et al.*, 1978) and fluctuating oxygen isotope values in an ice core from central Greenland have been used to detect a major transition which occurred in less than 100 years (Oeschger, 1984). Many hypotheses have been advanced which suggest mechanisms for rapid response. Two of the more popular are ice sheet collapse (Hughes, 1975 and 1981) and surging of portions of the ice sheet (Wilson, 1969; Budd and McInnes, 1978). Each of these theories has some amount of modeling to support the conclusions but, without exception, each model made gross assumptions about various aspects of the ice flow.

Ice flow is not easy to model. It is highly non-linear; the flow rate is very sensitive to the stress applied. Therefore, small changes in the shape of the ice sheet can cause large changes in flow rates. A further complication is that ice moves not only by deforming by the force of gravity but also by sliding over the underlying surface. Modeling of ice sheets controlled by deformational flow has been quite successful. Led by Mahaffey's (1976) model of the Barnes Ice Cap, Budd and Smith (1981) and Oerlemans (1982) have developed similar models which appear to do a good job of simulating the large-scale fluctuations of the Antarctic and Laurentide ice sheets. Birchfield and others' (1981) model of the Northern Hemisphere's ice ages shows the importance of isostatic response of the lithosphere in the initiation of each glacial phase.

For the Antarctic simulation, however, these results must remain suspect because they neglect the primary process of ice sheet discharge: ice streams. Ice streams are akin to rivers of fast-moving ice flowing past much slower ice. A single ice stream in Greenland drains about 5% of the entire sheet (Bindschadler, 1984). In Antarctica, the majority of the ice is funnelled into ice streams, which, in turn, feed separate or composite ice shelves—thick slabs of floating ice which eventually generate high tabular icebergs at their seaward margins. The flow of the ice shelves must overcome drag at the sides of the embayment, drag across any isolated bedrock high spots, and the resisting force of the sea. It is these forces which retard the flow of the ice stream. While a change in snowfall rates or atmospheric temperature will eventually affect the flow rates, and therefore the shape, the time scales are of paleoclimatic significance (Whillans, 1981). A possible exception to this statement is if the warmed surface of the ice sheet experiences extensive melting, in which case large amounts of water may be released into the oceans. For those broad regions of ice sheet controlled by the ice stream-ice shelf system, the response can be on a time scale perhaps as short as a century. Here the key is the ice shelf. Unlike the ice sheets, the ice shelves are exposed to the sea; any change to the resisting forces such as a rise in sea level or an increase in the rate of basal melting (caused by warmer ocean temperatures or an altered circulation pattern) would allow an increase in the discharge of ice from the ice sheet. If begun, this process is potentially unstable since increased ice discharge causes increased sea level. It is precisely this instability which has caused so much attention on the West Antarctic, where most of the ice rests on bedrock far below sea level (Mercer, 1978; Hoffman, 1983; National Academy of Sciences (NAS), 1985).

For all that is known about the existence of this potential instability, adequate modeling of this scenario still does not exist. However, pieces of the puzzle have been developed. MacAyeal and Thomas (1983) have designed an ice shelf model which provides a good simulation of the flow rate on the Ross Ice Shelf. MacAyeal (personal communication) has now succeeded in making this model time dependent and is studying the process of the ice shelf becoming grounded. Some models of ice stream flow exist (Bindschadler and Gore, 1982; Budd and McInnes, 1978; Weertman and Birchfield, 1983), but all such models are limited by the absence of knowledge of the dynamic controls of stream flow. Field research is currently underway in West Antarctica to help answer some of these unknowns. Some attempts have already been made at modeling the ice stream-ice shelf process (Denton and Hughes, 1981; Thomas *et al.*, 1979) but each has made extreme assumptions which qualify the results. This new generation of models holds the promise of coupled ice sheet/climate models which will preserve the essential ice dynamics and adequately predict its response to all boundary conditions.

4. Land Surface Processes

Land surface processes important to climate models are the fluxes of heat and water through the soil-vegetation-atmosphere strata and of momentum at the land-atmosphere interface. These are dependent on certain characteristics of soil and vegetation such as albedo, surface roughness, and masking depth. These characteristics and processes have to date been relatively crudely parameterized in GCMs. There is currently an effort to develop models of land surface processes, based on the underlying physics, for incorporation into GCMs and to improve the accuracy of the inputs from these models. A comprehensive review of land surface considerations in atmospheric general circulation models is available (Eagleson, 1982).

The major process to be modeled is the (surface) hydrologic cycle, including the dynamics of both soil and vegetation water use. The amount of water that is available for evaporation in turn influences the surface and ground temperatures, as part of the heat flux in the form of latent heat. Besides the albedo, masking depth, and surface roughness characteristics mentioned above, other soil and vegetation data needed as exogenous variables for GCMs include: hydraulic conductivity, porosity, and field capacity for soil; and leaf area index, rooting density, canopy interception of precipitation, and canopy resistance for vegetation. The seasonal variations of the vegetation characteristics are also needed.

Hydrologic cycle. Previous models have used simple field capacity designations with an evaporation efficiency factor to account for evapotranspiration. Several GCM groups have initiated efforts to incorporate more realistic ground hydrology models into the large models (Dickinson, 1984; Mintz and Sellers, private communication; Zobler and Choudhury, private communication). Although approaches differ, particularly as to the degree of complexity to be modeled, equations of fluid dynamics and thermodynamics are used to model the hydrologic cycle from first principles.

One approach to the hydrologic processes involves a soil-canopy water model based on the Richards equation (Jensen and Hanks, 1967). With the input of soil, climate, and vegetation data, rainfall in such a model is intercepted by the vegetation canopy and the ground surface. Rain infiltrates into the top soil layer based on soil properties. The excess above infiltration, canopy catchment, and surface ponding runs off as a function of slope (conceptualized as streams) to lakes and to the ocean. In the ground, the water moves as saturated or unsaturated conduction between layers and some may run off as ground water. Water also may move upward because of the potential gradients or by root absorption and plant conduction to evaporate at the soil or leaf surface.

This approach can incorporate a complete evapotranspiration model based on the equation of Monteith (1981), which is a modified form of Penman's (1948) equation for evaporation over open water. The Monteith equation accounts for canopy resistance as well as boundary layer resistance. The evapotranspiration model differentiates vegetation types through differences in leaf area index, leaf resistance, and rooting density. Water is drawn from the soil, which can be divided into a finite number of layers. Inputs to the model are net radiation at the canopy, vapor pressure deficit, and canopy resistance, which is a function of leaf resistance, leaf and soil water potential, air temperature, leaf area index, and global insolation. Leaf water potential dependence can be eliminated by equating water uptake by plant roots to water loss by the atmosphere (Choudhury, 1984).

Problems to be solved in the accomplishment of this modeling approach (besides the accurate inputs needed for the physical characteristics of soil and vegetation) include the need for acceptable ways to spatially integrate the heterogeneity of soil and vegetation types and properties within the coarse grid of the GCMs, and the need to parameterize the atmospheric inputs defined only for the coarse grid to sub-grid hydrologic scale, i.e., how to accurately partition precipitation into runoff, canopy and surface storage, ground water, soil moisture, and evapotranspiration. The biggest problem in modeling the hydrologic cycle relates to asssessing the role of vegetation. It is unclear to what extent vegetation biodynamics should be included in global climate modeling. Sensitivity tests must be performed to determine the vegetation parameters to which climate models are most responsive.

Land-surface data bases. Modeling the land surface processes must be done with concurrent development of appropriate data bases. Soil and vegetation classifications have been digitized at a 1° resolution (Matthews, 1983; Zobler and Cary, 1984), with type, texture, and slope for soil and spatially dominant natural vegetation and land use for vegetation. Now, further characteristics which affect the hydrologic processes must be collected. Data availability is most limiting in respect to modeling transpiration. Ideally, the following data should be available for either dominant or representative species for each vegetation type: stomatal, leaf, and canopy resistances in relation to soil water potential, seasonal variation of leaf area index, root density in relation to depth of soil, and interception of precipitation.

The specification of albedo is fairly well accomplished for snow- and ice-free surfaces. It has progressed from a two-component land/ocean prescription (used by Arakawa, 1972) and a latitudinal or geographical prescription often based on global distributions of surface albedo published by Posey and Clapp (1964). Some current GCMs utilize digital data bases of vegetation types with seasonal albedo specifications constructed from reported measurements of albedo, spectrally discrete reflectances, and ratios of near-IR/visible reflectances (Matthews, 1984). Efforts for improved specification of albedos now involve wet and dry soil differences and seasonal variations in vegetative and soil percent covers (Dickinson, 1983). In the future, albedo specification will ideally involve the spatial integration of sub-grid-scale differences in soil types from a digitized soil data base (Zobler and Cary, 1984). Improved data collection and availability from satellite sources are also aiding in the specifications of both snow- and ice-free and snow- and ice-covered albedos for climate modeling purposes.

Other land surface characteristics to be specified in GCMs are masking depth and surface roughness. There is an interactive effect on albedo between depth of snowfall and vegetation height and density. Masking depth is used to parameterize this interaction. Masking depth is defined as the snow depth, given in equivalent thickness of liquid water, at which the albedo of pure snow (which varies with snow age) completely ''masks'' the albedo of the underlying ground. Larger masking depths are defined for tall, dense vegetation types, smaller masking depths for short, sparse types. Surface roughness, another land characteristic, describes the ability of a surface to absorb momentum from the air moving over it. In a global climate model, it is related to vegetation in lowland regions which are covered by forests of significant height, e.g., the Amazon Basin. Roughness length values have been compiled from the literature.

Present efforts to model land surface processes for GCMs involve two major tasks: first, to evaluate the impact of land surface processes, particularly evapotranspiration, on climate simulations through appropriate sensitivity tests; and second, to concurrently develop appropriate data bases for use as inputs to those models due to the extreme heterogeneity of soil and vegetation types.

5. Planetary Boundary Layer

The planetary boundary layer (PBL) is the layer adjacent to the earth's surface within which vertical turbulent transports play a dominant role in the budgets of momentum, moisture, and sensible heat, and the turbulence energy is more-or-less continuously distributed in space and time.

In the early years of general circulation modeling, the PBL ws recognized as an important dissipation site (Charney and Eliassen, 1949), and as a significant regulator of the surface fluxes of sensible heat and moisture (Smagorinsky *et al.*, 1965). Meanwhile, pioneering observational studies revealed the intimate coupling between the tropical PBL and the cumulus layer above (Bunker *et al.*, 1949; Malkus, 1954), and the crucial role of tropical cumulus convection in the global energy cycle (Riehl and Malkus, 1985; Riehl and Simpson, 1979).

Then, during the 1960's and 1970's, Lilly (1968) drew attention to the remarkably persistent marine subtropical PBL stratocumulus decks, and Herman and Goody (1976) described the similar PBL stratus layers of the Arctic summer. During these same years, much effort was devoted to understanding how the PBL turbulence is influenced by the variability of PBL depth, and the processes that produce that variability. Deardorff (1970; 1972; 1974a, b) showed that the PBL depth is determined by a rate equation in which turbulent entrainment plays a leading role, and that the stability dependence of the surface transfer coefficients can be expressed in terms of a bulk Richardson number which is proportional to the PBL depth. Arakawa and Schubert (1974) argued that the PBL depth tends to be reduced by the action of cumulus cloud ensembles, which carry PBL mass up into the cumulus layer. They also pointed out that a deep PBL is favorable for cumulus activity.

As a result of these studies, the PBL is now understood to be much more than a near-surface layer of strong turbulent transports and kinetic energy dissipation. It serves as a variable-depth reservoir of moist air, and as a regulator for the tropical and mid-latitude-summer cumulus layers (Randall, 1980a,b), which are important features of the climate in their own right, and which dominate the radiation balance where they occur (Suarez *et al.*, 1983).

It is natural that some of the most important PBL processes are cloud related. A large portion of the solar energy absorbed by the earth is introduced into the atmosphere through surface evaporation, in the form of latent heat. Because the PBL controls the evaporation and turbulent redistribution of water substance into the atmosphere, it strongly determines the global distributions of both cumuliform and stratiform clouds. The clouds, in turn, influence the mean structure and turbulence of the PBL through cloud-induced circulations, through the radiation field, and through precipitation. A comprehensive simulation of PBL processes for a numerical model of large-scale atmospheric circulations must therefore include a simulation of the interaction of the PBL with clouds. This aspect of the PBL parameterization problem has an importance comparable to that of the determination of the turbulent fluxes.

The problem of PBL parameterization for global circulation models therefore goes far beyond the problem of parameterizing the turbulent fluxes. The structure and variable depth of the PBL must be recognized, not only to determine the stability and storage capacity of the PBL, but also in the design of cumulus parameterizations. At the same time, the effects of cumulus activity on the PBL must be taken into account. The observed PBL stratus layers must be reproduced in any comprehensive climate simulation, and their very powerful effects on the PBL turbulence must be parameterized realistically.

Furthermore, it is not enough to develop a physically sophisticated (and correct) model of the PBL which allows calculation of the response of the PBL to a given state of the free atmosphere. We must also carefully simulate the feedback and control mechanisms which determine the evolution of the free atmosphere and the PBL as a coupled physical system. This is possible only through careful design of the mathematical coupling between the parameterized PBL processes and the predicted variables of the numerical model.

III. STATE OF THE ART OF CLIMATE DATA ANALYSIS METHODS

No modeling program would be considered healthy if it operated independently of observational data. Often relations originally found in data become the foundation of a new thrust in a modeling program. It is then necessary to assess the state of the art of data analysis methodology in order to fully appreciate the state of climate theory. The methods used in studying the output of climate model runs are often similar to those used in studying the data of the real climate. Hence, some attention will be devoted to those problems in this section as well.

A. Basic Measures of Climate

The most fundamental test of any climate model is its ability to reproduce the first-order statistics of the atmosphere, ocean, or ice. These include the ensemble means of the seasonal cycle of many predictive variables such as the temperature at some height. Such data are often displayed as monthly averages of zonal averages. Maps of these ensemble means can also be contoured. Perhaps the most useful representation of the seasonal cycle is to display contour maps of the various time harmonics of the cycle. For example, Short *et al.*, (1984) displayed the mean annual and annual harmonic for the outgoing terrestrial radiation as measured from Nimbus 7. This makes for easy and convenient comparison with model output, e.g., North *et al.*, (1983a). Similar use has been made of the harmonics of the temperature field by White and Wallace (1978). Use of these statistics in climate models can be much more revealing than a simple comparison of the simulation for a single month, since different processes dominate at the different time scales, and pinpointing model deficiencies can be greatly facilitated by such an analysis. For example, in the energy balance model of North *et al.*, (1983a) it was found that the first and second harmonic of the temperature field agree much better with the data than the mean annual distribution over the globe; the difficulty could easily be traced to the lack of inclusion of such features as the Gulf Stream, which does not vary significantly on a seasonal basis but is very important in the mean annual temperature distribution. Although this technique has never been applied to the testing of GCMs, it is likely to be useful.

B. Variances

A more stringent test of GCM validity is the comparison of second-order statistics such as variances and covariances with observational data. The range of possible second-order-moment data is enormous and encompasses nearly every aspect of climate. Much of the rest of this section is therefore devoted to this class of data analysis problems.

The most straightforward second-order statistic is the variance of a quantity at each point in the atmosphere (ocean-cryosphere). Such comparisons with data are now routine. One interesting point needs to be stressed in the analysis of variances, that is, the time scale under consideration. Most climate variables vary on a continuous spectrum of time scales, and, if we look at, say, monthly averages of a quantity, we are applying what amounts to a filter to the time series and such a filtering process will include contributions from shorter time scales than one month giving rise to a variability of monthly means even though there may be in effect no (or at most red noise) interannual variability. Such misleading but natural and unavoidable variability of monthly means is called climatic noise (Leith, 1973), and it effectively sets a lower limit on the size of signal that can be detected or usefully predicted in a particular forecast. This effect has been studied extensively by Madden (1981) for conventional meteorological data and recently by Short and Cahalan (1983) using the infrared data analyzed earlier by Cahalan *et al.*, (1982) from the NOAA operational satellites.

C. Covariances

The estimation of the climatic noise level requires first estimating the time-lagged autocorrelation function for the variable in question. Cahalan *et al.*, (1982) used twice-daily IR data which were gridded on 2-by-2 degree squares. These time series are primarily a measure of the day-to-day cloudiness fluctuations although low-frequency surface thermal variation can also be detected. With cloudiness variability now being seriously included in GCM studies it seems appropriate that this second-moment-statistic field be included in the tests of GCMs. Stochastic models involving advected red noise were found to represent the data satisfactorily enough that such an approach might prove useful in GCM parameterization.

In examining the second-order statistics it is often useful to somehow remove the seasonal cycle. Blackmon (1976), in examining a 10-year data set, removed the seasonal cycle by first constructing a periodogram of the data, then deleting the first four harmonics of the annual cycle, finally recomposing the time series. Although very appealing and probably very useful in many applications this procedure is not correct since it is based implicitly upon a linear model of the system and these time series are surely generated by highly nonlinear mechanisms. For example, the variance of the temperature is strongly modulated by the annual cycle and the Blackmon procedure does not remove such an effect. Clearly, work needs to be done on the problem of seasonal adjustment.

Spatially distant correlations are also an interesting second-moment measure of climate. Cahalan *et al.*, (1982) showed that for the higher-frequency cloud fluctuations the e-folding radius for such an autocorrelation was about 10 degrees on a great circle and surprisingly isotropic over the Pacific. Similarly, in the optimum interpolation, e.g., Gandin (1963), of meteorological fields for initializing forecasts, spatially separated autocorrelation statistics are needed. Similar bell-shaped autocorrelation functions are found except that the range is larger by about a factor of two for such fields as the geopotential height.

It has been known for over 15 years that if time-averaged data are used instead of daily data the range of significant correlation can be truly planetary (teleconnections). Hence, lower-frequency phenomena have long-range autocorrelations that are not monotonically decreasing, but rather seem to be associated with quasi-stationary wave-trains. Lau and Chan (1983) have used monthly averages of the same NOAA satellite data to detect the same long-range teleconnections in cloudiness. The advantage of the satellite data is that the cloudiness signature is so much stronger than geopotential height anomalies that far fewer years (7 versus 30) of data are needed to achieve statistically significant signal-to-noise ratios. A stochastic model has been developed to fit these data (Lau, 1984), which should prove useful in classifying the types of theories that are consistent with the El Nino/Southern Oscillation phenomena.

D. Eigenvectors

The most natural way to study stochastic fields like those encountered in climatology is by means of the eigenvectors of the cross-correlation matrix, the empirical orthogonal functions (EOFs). These basis functions can be potentially useful in several applications such as compacting data sets (Kutzbach, 1967), serving as predictors (Barnett and Hasselmann, 1979), and in the physical interpretation of data (Wallace and Gutzler, 1981). Unfortunately, sampling errors tend to distort the patterns found from data sets that are too short in length (North *et al.*, 1982), and measurement errors can also contribute to significant errors as well (Cahalan, 1983). The physical interpretation of EOFs is now clear (North, 1984) in that a number of physically interesting systems driven by noise have their solution EOFs coinciding with their normal mechanical modes. The exceptions to this rule are easily understood in terms of linear instability theory. Unfortunately, the real climate system is highly nonlinear and the linear analogies do not in general hold. More work needs to be done in the area of understanding nonlinear stochastic systems.

EOFs can also have interesting time behavior. North (1984) and Barnett (1983) have suggested schemes which may be equivalent for analyzing this dependence consistently. One scheme involves finding the eigenvectors of the cross-spectrum matrix and amounts to finding the EOFs at each frequency or time scale (North, 1984). Barnett's scheme involves the construction of complex EOFs. Both systems need to be checked for their stability to sampling and other types of interference with the estimation process.

Cross-spectral analysis has been applied to meteorological data (Pratt and Wallace, 1976) and to the output of GCMs (Shukla and Strauss, 1981). There remain several questions about what such an analysis means if the field (time series) is not stationary and not rotationally invariant on the sphere.

E. Hypothesis Testing

Our understanding of stochastic fields as applied to climatology and our ability to test whether they have changed significantly due to some external forcing is not in a satisfactory state. The most popular tersts are those using the student t test at individual points on a map, e.g., Chervin (1981). Hayashi (1982) has developed sampling theory for the signal-to-noise ratio, but it still depends upon point-by-point use of the student t test. It is well known that this test will be passed at some spots over the field even if the hypothesis is false. The likelihood of the test giving misleading results depends upon the number of independent degrees of freedom in the field; this last depends upon the long-range correlation structure of the field. Recently, attention has been focused on the application of the theory of multivariate statistics to get around this difficulty (e.g. Hasselmann, 1979), but these approaches are also very difficult to apply in specific GCM applications, (Hannoshock and Frankignoul, 1985). Another approach has been suggested by Livezey and Chen (1983) and Preisendorfer and Barnett (1983), namely Monte Carlo procedures. Clearly a procedure is needed which is both sensitive enough and economical. Livezey (1985) discusses the search for such a procedure at length.

Another approach has been taken by Bell (1982), who addresses the question of detecting climatic change due to an external influence when a specific prediction has been made by a GCM. He finds a single optimally weighted variable whose signal-to-noise ratio is largest. In this way he can test the hypothesis that the climate has or has not changed in agreement with the prediction. Bell's method needs refinement because the weights are based upon climatology and the sampling variations are yet to be studied.

IV. Climate Predictability Research: Experimental Climate Forecast Center

A. Background

The prediction of climate is a primary goal of climate modeling and analysis, but it is an enormous problem and can encompass a wide range of time scales. The activities of the Experimental Climate Forecast Center (XCFC) will focus on the time scales of interest (monthly, seasonal, interannual) defined by the Memorandum of Understanding (MOU) between NOAA's National Climate Program Office and NASA's Goddard Space Flight Center's Laboratory for Atmospheres (GLA), which established the second such Center at Goddard.

On the other hand, it is not possible to circumscribe climate prediction in space, even if one is only interested in a regional scale, like North America. This is because to a large extent regional climate anomalies are a consequence of globally teleconnected systems and events. Thus, climate prediction research must include all spatial scales. As a practical matter, the overall scope and particular regions selected for emphasis and level of effort will be prioritized and influenced according to relative importance, tractability, and, not least, data availability.

In the near term climate prediction research for the time scales indicated will of necessity require two rather independent approaches. For the shorter time scales up to and including inter-monthly, climate models of the GCM variety will be the primary approach for prediction and predictability studies. Prediction research is concerned with the extension of the state of the art in forecasting, while predictability studies have as their goal the definition of the ultimate prediction skill possible as better data sets and models are developed. For the somewhat longer time scales, which include seasonal as well as interannual time scales, statistical-dynamical models (SDM) and empirical methods will be expected to play a greater role. GCMs will be used on these time scales to refine our understanding of the roles of the underlying boundaries and the annual cycle in formation and maintenance of quasi-stationary circulation regimes with less emphasis on the role of internal dynamics through the initial conditions. In both cases, emphasis will be placed on the application of satellite data in climate prediction where appropriate.

Many of the forecast studies with GCMs will be natural extensions of the shorter medium-range forecasting research, i.e., five to ten days, in order to progress confidently to the monthly prediction problem. At the present time, 10-day numerical forecasts are computed daily at the European Center for Medium Range Weather Forecasts (ECMWF) and at the National Meteorological Center (NMC). While daily forecast skill does not on the average extend beyond about 6 days in the Northern Hemisphere and varies widely from day to day, there is substantial evidence that the planetary scales may be predictable well after individual synoptic-scale systems have ceased to be predictable (Kalnay and Livezey, 1984).

A key aspect of the medium-range prediction problem is that GCMs must properly forecast the low-frequency, large-scale signals observed in the atmosphere. These modes include such diverse behavior as index cycles, the Pacific/North American pattern, the North Atlantic Oscillation, blocking, the Southern Oscillation, and the Monsoon. Several observational studies have helped to quantify these signals (see, for example, Wallace and Gutzler, 1981; Schubert, 1984a; Barnett, 1984) while recent studies based on simplified models are beginning to shed light onto the nature of these modes (see, for example, Frederiksen, 1982; Simmons *et al.*, 1983; Schubert, 1984b). Such information is vital for providing direction and emphasis for model development leading to improved long-range forecasts made with GCMs.

B. Experimental Forecast Research

Climate prediction research will be carried out using available data bases. Validated climate data from both conventional and satellite sources will be used for initialization and model verification to the maximum extent possible to better evaluate state-of-the-art forecast skill and contrast it to new or other methods. This would include validated operational and research satellite products when and where such data are available.

The experimental forecast work described here partially focuses on related research already going on in the Laboratory for Atmospheres at Goddard and will be coordinated with these other climate research activities. The level of attention this problem receives, however, is currently being increased.

1. GCM Medium- and Extended-Range Prediction Research

Large numbers of 10-day forecasts produced by GLA, ECMWF, and NMC GCMs have been acquired and form the basis for studying potential ways to improve medium- and ultimately extended-range 10-30 day prediction.

Almost all of present-day skill in monthly prediction is the result of insight about the average conditions in the first week of the month. This insight is principally a consequence of time-averaged charts produced from medium-range forecast runs like those that have been archived at GLA. Thus, the natural starting point for improving monthly forecasts with GCMs is the enhancement of information obtained from these shorter runs. Such enhancement then may further motivate longer integration times.

One approach to improving these forecasts is through continued development of global analysis and prediction systems. A team of researchers at GLA (not directly concerned with XCFC problem areas) responsible for this development will continue to pursue the general goal of applying space observational data to overall short- and medium-range forecast skill improvement.

The XCFC will emphasize two other approaches to improving medium- and extended-range forecasting. The first one, ensemble forecasting, is basically a statistical post processing of model output. The lagged-average method of Hoffman and Kalnay (1983) and further refined by Dalcher, Kalnay, and Hoffman (1985) should be particularly useful because it not only provides a natural framework for correcting model systematic error and for filtering unpredictable scales, but also for predicting error growth in advance. This and other techniques are currently being studied and compared to the ECMWF and NMC forecast series.

Within this research emphasis will be placed on the stratification of error patterns and growth by the circulation regime reflected in initial conditions. Forecasters with advance knowledge of when and how a GCM is likely to fail have a tremendous advantage over those with knowledge only of gross ensemble errors. A variety of analytic and diagnostic tools are available to apply to this problem.

All of this extensive experience in lagged-averaging gained from the medium range should facilitate its application to longer ranges. This is likely to be important because long GCM integrations from global analyses only a day apart (and different only in synoptic and meso-scale detail) can differ substantially from each other in the planetary scales after 15 days or so (Miyakoda, *et al.*, 1983). This, lagged averages of series of these forecasts are likely to be superior (for prediction out to a month) to an average of runs from the same analysis but with different random errors (a Monte Carlo approach).

The second approach to improve medium and extended forecasting will be centered on the correction of systematic model forecast errors. One of the most obvious systematic errors is the well known tendency of the zonal flow to drift away from the observed climatology. This type of error has a crucial role in the accuracy of prediction beyond four or five days because, for example, the atmospheric response to anomalous boundary forcing depends strongly on the characteristics of the zonal flow. Fortunately, the zonal systematic error is also the easiest one to determine by statistical sampling. The XCFC will attempt to establish the nature of the systematic error in the zonally averaged fields and to correct it. For this purpose, in addition to improvements in the physical parameterizations, introducing empirical corrections *during* model runs is planned. This approach has not yet been tested and requires preliminary work to demonstrate its feasibility. Meanwhile, a sufficiently large set of 10-day forecasts from the GLA Fourth Order GCM will be available to estimate the model's climate drift and serve as control for subsequent runs.

2. GCM Prediction and Predictability Studies up to Inter-Monthly Range

The approach for predictions up to one or two months will be to systematically explore the existence, if any, of predictability of time-mean anomalies associated with initial conditions (dynamic or internal variability) and with anomalies in the boundary forcing, which introduce external variability. This will be done by means of a series of numerical integrations of the Goddard Laboratory for Atmospheres Fourth Order GCM, using real initial conditions corresponding to different years, and boundary conditions corresponding both to climatology and to observed anomalies for the same years.

Planned activities include building a basic series of experimental 45-day integrations whose results will be made available to the research community. Several integrations (up to 10) of each 45-day set will be produced, each set starting with initial conditions corresponding to a different year. The experiments will be performed first for winter and summer and later for the other two seasons.

The basic experimental sets using the multiple integrations will involve three sets of initial conditions, with each having a specific objective. First, *observed* initial conditions but with climatological boundary conditions will be used. The purpose of this experiment is to determine how much, if any, prediction skill can correctly be ascribed to the initial state of the atmosphere. This amounts to a determination of the seasonal variation of the model's systematic error, including but not limited to its climate drift. A by-product will be an estimate of the model's climate noise, for use in sensitivity or other experiments in which ensembles of model runs are compared. Second, integrations will be performed with the *same* initial conditions, but also appropriate observed boundary forcing. The purpose here will be to evaluate the reduction in error in specifying the anomalous circulation that can be achieved by addition of boundary forcing. Third, the second set of integrations already described will be repeated with superimposed errors. Here, the purpose will be to estimate the joint predictability derived from both initial and boundary conditions. This latter experimental approach may be thought of as a way to ascertain the upper limit of predictability available from the present model.

Other series of experiments will be run from the same set of initial conditions and compared to one or another of the sets above depending on the outcome of the first three sets as well as feasibility experiments run with simpler, but more efficient, global models, or a larger sample of shorter GCM runs (like those described under 1. above). Such experiments will be the result of successful preliminary experience with ideas like lagged-averaged prediction, within-run empirical correction of climate dirft, or more explicit direct model improvements. The length of these runs will largely be determined by the results of the initial sets of experiments.

These prediction/simulation experiments will be compared to each other as well as with the observed atmospheric circulation and serve as partial data bases for work under 3. below. Not only will they be useful for the prupose of studying predictability, but also for determining the GCM strengths and weaknesses, systematic errors, sensitivity to boundary conditions, etc. Collaboration with academic researchers will be particularly useful in this respect.

3. Prediction Studies at Seasonal to Inter-Annual Time Scales

Moving from monthly to seasonal and interannual time scales, the role of the ocean and ocean-atmosphere interaction becomes increasingly important. The integration of fully coupled systems with state-of-the-art atmosphere and ocean GCMs for interannual time scales is still rather problematic. Because atmosphere GCMs and ocean GCMs are individually tuned to the present climate, the process of coupling often aggravates the climate-drift problem (Gates *et al.*, 1984). Therefore, a long-term integration of coupled GCMs does not always guarantee meaningful results. In view of these considerations, the studies of seasonal/interannual variability at present must rely strongly on empirical data analyses and use of simple statistical dynamical models (SDM) to help establish the physical bases for predictability at seasonal/interannual time scales. Nevertheless, key aspects of the roles of both lower boundary anomalies and the annual cycle for events like the 1982-83 *El Nino* and the Summer 1980 North American heat wave and drought will benefit substantially from GCM studies. These include sensitivity and simulation work similar to much of that described under Chapter II of this report. Thus the XCFC will give these kinds of studies the attention they warrant.

One of the key elements in the seasonal/interannual variability of extratropical climate is its apparent teleconnection with tropical convection. For example, Horel and Wallace (1981) and studies by many others have pointed to a heat source over the equatorial central Pacific which drives a wave-train perturbation in geopotential height, surface pressure, temperature, and rainfall from the source region to North America. Thus the understanding of tropical variability especially in the least-measured parameter (rainfall), becomes a prerequisite in the study of predictability of global climate on the seasonal/interannual time scales. It is in this aspect that satellite observations are essential for adequate measurements in this critically important region of the earth's atmosphere. A recent series of studies by Lau and Chan (1983a, b), Lau and Chan (1985), and Lau and Phillips (1985) provide one example that satellite coverage can provide valuable information (earth radiation data) in the tropics which could not be derived from conventional data alone. Another promising data set that could be used to determine major areas of convection is the cloud climatology being developed under the International Satellite Cloud Climatology Project (ISCCP).

Of particular relevance to long-range prediction of climate is the finding from satellite-derived cloudiness fluctuations that a 40-50-day quasi-periodic ''see-saw'' exists in tropical convection over the western Pacific and Indonesian maritime continent. Extratropical circulation appears to interact with this convection pattern resulting in some upstream (over Eurasia) and downstream (over North America) influence. The morphology of these upstream and downstream anomalies agrees with the interpretation of Rossby wave dispersion and refraction on the sphere (Hoskins and Karoly, 1981). The spatial structure of the downstream anomaly resembles closely that of the Pacific-North American pattern which has been related to a number of El Nino/Southern Oscillation events—a global anomaly in the interannual time scale. Research should now be focused on the connection between the intraseasonal, e.g., the 40-50-day oscillation and possibly others and the seasonal/interannual variabilities.

Two approaches are now being considered. The first involves a further detailed study of the spatial and temporal structure of intraseasonal tropical-midlatitude interactions. Empirical (normal) modes of variation will be examined to estimate seasonal/interannual signal-to-noise ratios and hence potential predictability limits. The second approach involves the use of simple stochastic-dynamical models which mimic the gross statistical characteristics of the real system. By thoroughly studying such simplified systems, inference may be possible of some general characteristics which may be tested against theory and help interpreting GCM results. As an example, in the monthly up to seasonal time scales a combined statistical and dynamical approach has been developed by Schubert (1984a,b) in the form of a two-level simplified GCM which utilizes EOFs as a basis set. For interannual time scales, Lau and Chan (1983a,b) have developed a nonlinear stochastic model for El Nino type events. Preliminary results demonstrate that while there is a lack of predictability of the actual time of onset of an El Nino/Southern Oscillation (ENSO), there is, during the course of the ENSO, a possible upper limit for seasonal predictability of about 6-9 months.

Considerably more research and generalized experiments in this non-GCM area will be required to provide the physical bases for specific experimental forecasts. This effort is now being actively pursued.

V. SUMMARY OF CLIMATE MODELING RESEARCH OBJECTIVES (1985-1995)

FY85

- Assessment of climate impact of stratospheric aerosols from Mount St. Helens and El Chichon volcanic eruptions
- Begin construction of experimental climate forecasting case library

FY86-88

- Expand observing system simulation experiments in support of Eos and TRMM
- Improve parameterization of clouds in climate models as part of the First ISCCP Regional Experiment (FIRE)
- Intensive studies of the Earth's radiation budget using ERBE and ISCCP data sets
- Studies of land-atmosphere processes associated with persistent regional-scale climate episodes (e.g., the Sahel drought)
- Studies of quasi-stationary structures (e.g., blocking)

FY89-91

- Major improvements in coupled ocean-atmosphere climate models
- Improved parameterization of the planetary boundary layer in climate models
- Intensive studies of El Nino/ Southern Oscillation phenomena
- Improvements in running efficiencies for climate models

FY92-95

- Critical assessment of the potential limits of climate predictability
- Comprehensive climate prediction experiments (interannual time scale) using fully coupled models with global data sets acquired by research satellites, operational satellites, and Eos

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APPENDIX A

List of Acronyms

AIDJEX	Arctic Ice Dynamics Joint Experiment
DMSP	Defense Meteorological Satellite Program
ECMWF	European Center for Medium Range Weather Forcasts
ENSO	El Nino/Southern Oscillation
EOF	Empirical Orthogonal Function
Eos	Earth Observing System
ERBE	Earth Radiation Budget Experiment
FIRE	First ISCCP Regional Experiment
GCM	General Circulation Model
GLA	Goddard Laboratory for Atmospheres
GOES	Geostationary Operational Environmental Satellite
IR	Infrared
ISCCP	International Satellite Cloud Climatology Project
LAF	Lagged Average Forecasting
MOU	Memorandum of Understanding
NMC	National Meteorological Center
NOAA	National Oceanic and Atmospheric Administration
PBL	Planetary Boundary Layer
PNA	Pacific North American
SDM	Statistical Dynamical Model
SST	Sea Surface Temperature
TIROS	Television and Infrared Operational Satellite
TRMM	Tropical Rainfall Measuring Mission
UARS	Upper Atmosphere Research Satellite
UCLA	University of California, Los Angeles
WCRP	World Climate Research Program
WMO	World Meteorological Organization
XCFC	Experimental Climate Forecast Center

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15. Supplementary Notes

16. Abstract

The emphasis of the NASA strategy for climate modeling and predictability research is on the utilization of space technology to understand the processes which control the earth's climate system and it's sensitivity to natural and man-induced changes and to assess the possibilities for climate prediction on time scales of from about two weeks to several decades. Because the climate is a complex multi-phenomena system, which interacts on a wide range of space and time scales, the diversity of scientific problems addressed requires a hierachy of models along with the application of modern empirical and statistical techniques which exploit the extensive current and potential future global data sets afforded by space observations. Observing system simulation experiments, exploiting these models and data, will also provide the foundation for the future climate space observing system, e.g., Earth observing system (EOS), 1985; Tropical Rainfall Measuring Mission (TRMM) North, et al. NASA, 1984.

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