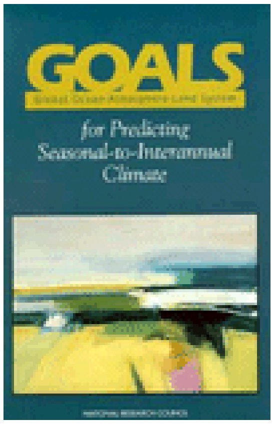

GOALS (Global Ocean-Atmosphere-Land System) for Predicting Seasonal-to-Interannual Climate: A Program of Observation, Modeling, and Analysis

Climate Research Committee, National Research Council

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GOALS Global Ocean-Atmosphere-Land System for Predicting Seasonal-to-Interannual Climate

A Program of Observation, Modeling, and Analysis

Climate Research Committee
Board on Atmospheric Sciences and Climate
Commission on Geosciences, Environment, and Resources
National Research Council

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Preface

The 10-year international Tropical Ocean and Global Atmosphere (TOGA) program was a major element of the World Climate Research Program (WCRP) with participation by the United States and many other countries. As TOGA approached its midpoint in 1989, two realizations with respect to the program had begun to emerge. The first was that, despite the remarkable progress already made, 10 years would not be long enough to achieve fully the objectives of TOGA's observational, modeling, and prediction components. The second realization was that climate variations on seasonal-to-interannual time scales seemed to be intimately linked with variations in extratropical sea-surface temperature (SST) and land-surface properties. This second realization cast attention on the possibility of acting on the achievements of TOGA to expand the area of inquiry beyond the tropical Pacific Ocean, where TOGA had concentrated its efforts, to the rest of the globe.

To consider both of these matters, the TOGA Panel of the National Research Council met with the Scientific Steering Group of the international TOGA program on 23–24 July 1990, in Kona, Hawaii. There, the TOGA Panel recommended that, to exploit the scientific advances made in understanding the dynamics of the coupled tropical ocean and global atmosphere system, a follow-on program to TOGA should be created to focus on global climate variability at seasonal-to-interannual time scales.

Toward this end, the TOGA Panel organized a series of study sessions. These covered the Asiatic monsoons, air–sea interaction in the tropical Atlantic, and the role of extratropical SST variations. On the basis of conclusions drawn from these study sessions, the TOGA Panel then proposed to the National Research Council's Climate Research Committee (CRC) that the CRC initiate a program as a follow-on to TOGA. That program, described in this volume, is called GOALS—the Global Ocean–Atmosphere–Land System program. GOALS is envisioned as supporting the new, international, 15-year program—CLIVAR (Climate Variability and Prediction program)—about to be launched by the WCRP.

In response to the TOGA Panel's suggestion, the CRC formed a GOALS steering committee (David L.T. Anderson, Michael Ghil, David Halpern, Edward S. Sarachik, Jagadish Shukla, and J. Michael Wallace) to explore further the ideas presented by the TOGA Panel and to engage a broader community of scientists. This Steering Committee planned the GOALS Study Conference, which was held at the East-West Center in Honolulu, Hawaii, on 1–3 March 1993. (The agenda and a list of participants appear in Appendix B of this report.) Attended by 110 scientists, the conference was organized around a number of scientific questions, each of which was addressed by an invited speaker. Taking into account the presentations and discussions at the conference, the Steering Committee assisted the CRC in preparing the GOALS science plan presented here.

The GOALS plan is for a 15-year (1995–2010) research program that builds on the success of TOGA. The plan calls for an expansion of observational, modeling, and process research to include the possible influences of the global upper oceans and time-varying land moisture, vegetation, snow and sea ice. We expect GOALS would be an important component of the CLIVAR program, and that it would benefit greatly from close cooperation with other research programs of the WCRP. We believe that a successful GOALS program would lay the foundation for a scientific basis for dynamical prediction of climate variations at seasonal-to-interannual time scales.

For their assistance in the production of this report, we are indebted to the staff of the Board on Atmospheric Sciences and Climate.

JAGADISH SHUKLA, CHAIR
GOALS STEERING COMMITTEE

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Executive Summary

This report presents a strategy for improving the understanding and prediction of climate variations on seasonal-to-interannual time scales. It proposes the launching of a new program called Global Ocean–Atmosphere–Land System—or GOALS—to build on the successes of the Tropical Ocean and Global Atmosphere (TOGA) program by broadening the geographic scope from the tropical Pacific to the global tropics and eventually to the entire globe. The 10-year TOGA program focused on understanding the coupled atmosphere–ocean system and the interaction between the tropical oceans and the atmosphere, typified by the El Niño/Southern Oscillation (ENSO) phenomenon.

Even modest improvements in climate prediction at seasonal-to-interannual time scales would be of great social and economic benefit. The new capability of making tropical climate predictions a year or so in advance developed during TOGA is already proving valuable to the countries surrounding the tropical Pacific. The proposed program will require consideration on a global basis of the low-frequency variability of the atmosphere and its modification by global sea-surface temperature (SST); time-varying land moisture and vegetation in the tropics; and the effects of land, snow and sea-ice cover.

The ultimate scientific objectives of the GOALS program would be to:

- understand global climate variability on seasonal-to-interannual time scales;
- determine the spatial and temporal extent to which this variability is predictable;

- develop the observational, theoretical, and computational means to predict this variability; and
- make enhanced climate predictions on seasonal-to-interannual time scales.

The focus of the GOALS program is an assessment of the global interannual climate variation that can be understood, simulated, and predicted. The central hypothesis of the program is that variations in the upper ocean (including SST), soil moisture, sea ice, and snow, exert a significant influence on seasonal-to-interannual variations of atmospheric circulation and thus, the predictability of the circulation. Hence, both understanding variability and predicting climate at seasonal-to-interannual time scales will require accurate measurements of global surface and upper-ocean conditions as well as improved models to simulate their future evolution.

The GOALS program would be a phased project, expanding first into the global tropics (TOGA focused on the tropical Pacific). This expansion would be based on the hypothesis that the key to understanding and predicting seasonal-to-interannual variations is understanding and modeling the processes that determine variations in the locations, interactions, and effects of the major thermal sources and sinks for the atmosphere. Subsequent expansion to higher latitudes would be guided by the insights from empirical studies, modeling studies, and observations concerning seasonal-to-interannual variability in the extratropical atmosphere, upper ocean, and land surface.

The GOALS program is proposed for the period 1995–2010. Following the successful example of the TOGA program, it would have four major program elements: modeling, observations, empirical studies, and process studies. The success of the program would be measured by enhanced understanding of global climate variability and predictability on seasonal-to-interannual time scales, by the effectiveness of the observing system it developed for describing and predicting the climate system, by the increased ability to model the processes critical to seasonal-to-interannual variations, and by the skill developed in predicting these seasonal-to-interannual climate variations.

It is proposed that the GOALS program be an important component of the Climate Variability and Predictability (CLIVAR) program, which is a broader new initiative of the World Climate Research Program (WCRP) addressing the variability and predictability of the coupled climate system. The long-term success of GOALS depends on the development of collaborative partnerships with other WCRP initiatives, including the Global Energy and Water Cycle Experiment (GEWEX) and the World Ocean Circulation Experiment (WOCE).

1

Introduction

A new age of climate prediction is beginning as the groundbreaking effort of the 10-year (1985–1994), international, Tropical Ocean and Global Atmosphere (TOGA) program comes to an end. Before the TOGA program began, it was not possible to carry out even the minimal observational and modeling efforts needed to predict short-term (seasonal-to-interannual) climate variations. Now, 10 years after the inception of TOGA, the necessary observing systems and models are in place for a concerted effort to accomplish this objective of short-term prediction. The program proposed in this report—the Global Ocean–Atmosphere–Land System, or GOALS, program—is designed to capitalize on the observational and theoretical progress made by TOGA and to meet the new challenges of climate prediction.

The most familiar variation of the climate is the annual cycle. The change of seasons associated with the annual cycle is also perhaps the most predictable variation. In the middle latitudes, where the United States is located, this cycle is often described in terms of warm (or hot) summers and cool (or cold) winters. In the tropics, the annual cycle is more evident in changes in precipitation and winds. Most people assume that the annual cycle is well characterized and understood. When the TOGA program began, however, the regular progression of the seasons was not well described over much of the oceans. Significant gaps still remain in our understanding of the global annual cycle.

There is great societal value in the seemingly trivial forecast that the conditions for each season or month will be close to that period's climatological mean. However, the progression of the annual cycle is not identical from year to year. The deviations from the normal, or averaged, annual cycle are referred to as climate anomalies or variations. Skill in climate prediction is measured by how well forecasters predict the variations from climatological values. Prediction of climate variations with lead times of a season to a few years is the ultimate objective of GOALS.

This introductory chapter sets the scene for the proposed GOALS program. It outlines the developments that led to the establishment of TOGA, including the discovery of the phenomenon called ENSO—for El Niño/Southern Oscillation—as a major theme in climate research. Following are descriptions of TOGA, its major objectives, and its achievements, which have prepared the way for future developments.

Chapter 2 introduces the GOALS program proposed by the Climate Research Committee of the National Research Council (NRC). It explains that GOALS would expand upon the original TOGA focus by laying a broader foundation for dynamical prediction of global climate variability at seasonal-to-interannual time scales. The chapter presents the scientific objectives of GOALS and lists nine high-priority science questions that the program should address.

Chapter 3 discusses spatial variability and temporal variability as they relate to predicting climate on seasonal-to-interannual scales. With respect to spatial variability, the chapter discusses the complexity of interactions among the upper ocean, the atmosphere, and land, as well as the interactions between the tropics and extratropics, and the effects of all these interactions on climate. It then describes seasonal, annual, interannual, and decadal variability as they relate to GOALS objectives.

Chapter 4 highlights the four major elements—modeling, observations, empirical studies, and process studies—envisioned for GOALS. It outlines the general sequence in which the work of the program would proceed. A section on each of the four elements describes the challenges within that area and their relation to other components of the program.

The data acquisition and data management needs of GOALS are discussed in Chapter 5. The objectives for a detailed data management plan are set out. The scientific and programmatic linkages of GOALS to other ongoing and proposed research efforts are addressed in Chapter 6. Chapter 7 describes the organizational structure proposed for GOALS and the relationship of the U.S. program to CLIVAR, an international program on climate variability and predictability de veloped under the auspices of the World Climate Research Program (WCRP).

Appendices to the report provide: background material on the present status of short-term climate prediction (Appendix A), the agenda and list of participants at the March 1993 study conference organized by the GOALS Steering Committee of the Climate Research Committee (Appendix B), and a list of acronyms and other initials (Appendix C).

ENSO AND ITS IMPORTANCE

It is well known that day-to-day atmospheric fluctuations are not predictable beyond about 2 weeks because of the chaotic nature of atmospheric dynamics. However, it has also been recognized that there is predictability in the midst of chaos. The interactions among the various physical components of the climate system—namely, the atmosphere, the upper oceans, the land, and the cryosphere (snow and ice)—produce long-period variations in the climate system that enhance its predictability. In particular, the relatively slow-changing surface conditions lead to a predictable slow variation on the statistics of the atmosphere (Namias, 1969, 1975; Charney and Shukla, 1981; Shukla, 1984). These surface conditions include sea-surface temperature (SST), sea ice, snow cover, soil moisture, vegetation type, and surface-land temperature. An outstanding example of long-period climate variation is produced by interactions between the tropical oceans and atmosphere. The recognition that the coupled tropical ocean and global atmosphere is potentially predictable led to the establishment of the TOGA program, described in the next section.

Before looking at the beginnings of the TOGA program, it will be useful to discuss briefly four terms—Southern Oscillation, El Niño, La Niña, and ENSO (El Niño/Southern Oscillation).

Southern Oscillation is the term Sir Gilbert Walker (Walker and Bliss, 1932) coined in the early part of this century during his attempt to predict the year-to-year fluctuations of India's monsoon rainfall. He described the Southern Oscillation as:

> a complicated set of relationships extending over the southern hemisphere and a large part of the northern, including temperature and rainfall, as well as pressure. In general terms, when pressure is high in the Pacific Ocean, it tends to be low in the Indian Ocean from Africa to Australia.

We now know that Walker was observing the two phases that manifest the Southern Oscillation in the tropical Pacific—*El Niño* and *La Niña* , or the warm phase and the cold phase, respectively.

The most widely known of the two phases is El Niño, which has come into the popular vocabulary in recent years, partly because of the severity of some recent "warm episodes." For example, in 1972 an El Niño event along the coast of South America was accompanied by alarming declines in the anchovy population, which had major repercussions for the local fishing industry and the world commodities market (Barber, 1988). The winter of 1976–1977, which coincided with a warm episode, brought drought in California and record cold and fuel shortages in much of the central and eastern United States. And the most devastating El Niño of the past century was the 1982–1983 ENSO "event" (as the large-scale El Niño warm episodes have come to be called). The most recent ENSO events were in 1986–1987 and 1991–1992. Thus, El Niño has attracted worldwide attention in recent years with the vastness of its reach and the severity of the weather conditions and economic dislocations that accompany it.

Historically, however, it was quite the opposite perception that accounted for its name. El Niño (the Spanish name for the child Jesus) was used to refer to the southward-flowing current off the west coast of South America that appeared shortly after Christmas some years. Locally it would bring heavy rains, which in turn brought an abundance of vegetation—including crops, grass for grazing, and other products—that seemed like gifts.

It is now known that the anomalous surface-water temperatures off the South American coast during the El Niño and La Niña phenomena often extend thousands of kilometers offshore and are but one aspect of anomalous oceanic and atmospheric conditions throughout the tropical Pacific. This irregular alternation of anomalously warm and cold temperatures and the concomitant rainfall variations across the tropical Pacific Ocean are referred to as ENSO. The ENSO phenomenon occurs every 4 years or so. Although it is often irregular and develops in different ways, many of its slowly evolving features can be simulated and predicted by models that include only the tropical Pacific Ocean and the atmosphere above it.

It is now well understood that ENSO is a coupled phenomenon arising from interactions between the atmosphere and the ocean, so that dynamical simulation and prediction are based on coupled atmosphere–ocean models. The ENSO signal offers the best initial hope for climate predictions, and models are now beginning to be able to predict ENSO events in advance: the warm phases of the 1986–1987 and 1991–1992 events were predicted more than a year in advance by some models (though mispredicted by others).

Other important interannual variations of climate are due to processes and mechanisms other than those associated with ENSO. To achieve the objectives of predicting climate variations (for example, flooding and drought in the global tropics and in the midlatitudes), observations and scientific study must be expanded beyond the tropical Pacific. Nevertheless, the work of the TOGA program laid the foundation for future developments.

TOGA

TOGA evolved from loosely coordinated research efforts that gained momentum in the early 1970s. Pioneering empirical studies by Jacob Bjerknes provided evidence that the long-term persistence of the global climate anomalies (with respect to the averaged annual cycle) associated with Walker's Southern Oscillation (Walker and Bliss, 1932) is closely associated with slowly evolving SST anomalies in the eastern and central equatorial Pacific. Bjerknes argued that the periodic strengthening and weakening of the southeasterly trade winds affect equatorial SSTs, which, in turn, influence the large-scale patterns of precipitation. Bjerknes viewed the shifts in rainfall patterns as forcing for the global anomaly pattern embodied in the Southern Oscillation (Bjerknes, 1966, 1969).

During the 1970s[1], empirical studies of the tropical upper ocean led to the hypothesis that the evolution of equatorial SST anomalies during the onset of a warm episode in the eastern Pacific could be explained by a coupling between the decreasing southeasterly trade winds and equatorial wave activity in the tropical upper ocean through the mechanical forcing by surface wind stress (Wyrtki, 1975). Simplified numerical models of the upper ocean provided strong support for this hypothesis and provided an interpretation of ENSO that could be tested on the basis of more detailed field observations and dynamical numerical models (for example, Busalacchi and O'Brien, 1981).

At the same time, atmospheric scientists began to exploit the historical records of surface meteorological data collected from volunteer observing ships, as well as upper-air data. From these they obtained a more comprehensive and detailed picture of the spatial patterns of SST and surface-wind anomalies associated with ENSO (Rasmusson and Carpenter, 1982). Empirical evidence of remote connections between the tropical anomalies and the middle- and high-

[1] Many observations and analyses of the thermal structure and currents in the equatorial Pacific were obtained from the National Science Foundation's North Pacific Experiment (NORPAX) Program (1971–1980). NORPAX pioneered the use of expendable bathythermograph profiling from volunteer observing ships.

latitude atmospheric circulation in the Northern Hemisphere (Horel and Wallace, 1981) was supported by analytical and numerical investigations of the response of the atmosphere to imposed SST or heating anomalies characteristic of ENSO episodes (Hoskins and Karoly, 1981; N.-C. Lau, 1985).

Although plans to begin a concerted study of ENSO in these pre-TOGA years already existed, the intense warm episode of 1982–1983 galvanized the tropical climate research community into action. Several factors contributed to the new determination to understand and predict the ENSO phenomenon: this extreme episode of 1982–1983 started without being noticed; a number of measuring programs[2] were in place to capture the details of the evolving episode as never before possible; the episode was of particular interest because it differed substantially from the "composite event" previously described by Rasmusson and Carpenter (1982); and, finally, the climatic consequences of this episode were very large in scale.

The early to middle 1980s were marked by increased activities in measuring the atmosphere-ocean system[3] and understanding the coupling between the atmosphere and the ocean in terms of surface winds and SSTs, especially in the tropics. In the ocean, the observed equatorial thermocline variations (the thermocline being the level or layer of the ocean [usually above 300 meters in the tropics] where the temperature gets rapidly colder with increasing depth) were shown to be simulated reasonably by simple ocean models, when forced with the climatologically varying winds, determined from data collected over long periods from volunteer observing ships in the tropics and then subjectively analyzed into wind fields (Busalacchi and O'Brien, 1981; Busalacchi et al., 1983). This success indicated that it is only the largest-scale aspects of the wind fields that are responsible for the observed large-scale thermocline variations. The SST was shown to be reasonably simulated by ocean general circulation models (GCMs) in terms of the wind forcing and a parameterized heat-flux forcing at the surface (Philander and Seigel, 1985).

For the atmosphere, the simple Gill model (Matsuno, 1966; Webster, 1972; and Gill, 1980), its extensions (for example, Zebiak, 1986), and

[2] The Equatorial Pacific Ocean Climate Studies (EPOCS) and the Pacific Equatorial Ocean Dynamics (PEQUOD) programs were both ongoing at the time.

[3] Among these activities were SEQUAL-FOCAL (Seasonal Equatorial Atlantic Experiment or Francais Ocean et Climat dans l'Atlantique Equatorial), TROPIC HEAT, TIWE (Tropical Instability Wave Experiment), WEPOCS (Western Equatorial Pacific Ocean Circulation Studies), and EMEX (Equatorial Mesoscale Experiment).

atmospheric GCMs were proving able to simulate the large-scale aspects of surface winds in terms of the thermal forcing of the atmosphere. By the middle 1980s, it was becoming more widely accepted that SST anomalies in any of the three tropical oceans (that is, Atlantic, Indian, and Pacific) can, at least in principle, induce global patterns of atmospheric circulation anomalies. Predictability studies with atmospheric GCMs showed that the potential predictability of the tropical atmosphere is far greater than that of the extratropics (Charney and Shukla, 1981).

With elements of ENSO simulation in place and the will to understand being strong, the TOGA program was born, both nationally (NRC, 1983) and internationally (WMO, 1985). Its three overall objectives were (WMO, 1985):

1. To gain a description of the tropical oceans and the global atmosphere as a time-dependent system, to determine the extent to which this system is predictable on time scales of months to years, and to understand the mechanisms and processes underlying that predictability;
2. To study the feasibility of modeling the coupled ocean–atmosphere system for the purpose of predicting its variations on time scales of months to years; and
3. To provide the scientific background for designing an observing and data transmission system for operational prediction if this capability is demonstrated by coupled ocean–atmosphere models.

From the inception of TOGA, the interaction of the ocean and atmosphere in the tropics was recognized as a central issue in predictability and prediction.

The TOGA program began on 1 January 1985 and will end on 31 December 1994. Its progress was reviewed by the NRC (1990) and at an international conference held in 1990 (WCRP, 1990). The program has been remarkably successful in addressing the three TOGA goals stated above. However, it should be noted that essentially all the work and progress have been in and over the tropical Pacific Ocean. By focusing on understanding and predicting ENSO, the largest identified signal of interseasonal and interannual variability in the circulation of the atmosphere and the tropical Pacific upper ocean, the TOGA program was able to define clearly its observational requirements and to motivate process studies. Eventually, the requirements of the developing coupled atmosphere–ocean models established the priori ties for the communication, organization, and synthesis of the various TOGA data sets.

As a result of the TOGA program, the coupled atmosphere–ocean interactions responsible for the ENSO phenomenon are thought to be basically understood. It is now known that the atmosphere-ocean system over the tropical Pacific has some aspects that are predictable a year or more in advance. An observational system has been put in place to monitor the tropical Pacific and to provide the initial data for coupled predictions of aspects of the ENSO phenomenon in and around the tropical Pacific. Predictions are being made with simplified statistical and coupled models, and prediction systems are being developed with more complicated and inclusive general circulation models. (See Appendix A for a more complete description of the current status of seasonal-to-interannual prediction developed under the TOGA program.)

Two ongoing subprograms have been developed to address the goals of TOGA:

1. The TOGA Observing System and, in particular, the TOGA TAO (Tropical Atmosphere Ocean) array—a network of about 65 moored thermistor chains in the tropical Pacific measuring surface meteorological data and subsurface thermal data (Hayes et al., 1991); and
2. The TOGA Program on Prediction (T-POP), a national research program concentrating on seasonal-to-interannual predictions using coupled atmosphere–ocean models (Cane and Sarachik, 1991; Sarachik, 1991).

The TOGA program has also fostered a large international process study in the western tropical Pacific, the TOGA Coupled Ocean–Atmosphere Response Experiment (COARE) (Webster and Lukas, 1992). This process study is examining the mutual interactions between the ocean and atmospheric convective activity over the ocean and is addressing the coupled modeling of these interactions. An operational Pacific Ocean modeling and data assimilation effort designed to synthesize irregularly taken ocean data into dynamically consistent fields of information has been started and continues to be run at the Climate Analysis Center of the National Weather Service (Derber and Rosati, 1989; Leetmaa and Ji, 1989; Miyakoda et al., 1990). This effort has focused the attention of researchers on the problems of ocean-data assimilation and has been useful as a testbed for investigating the impact of operational ocean data.

The TOGA program has also initiated the planning for an Inter national Research Institute for Climate Prediction (IRICP; Moura, 1992). The proposed research institute will concentrate on the prediction of aspects of ENSO and on the successful utilization of these forecasts by countries directly affected by interannual variations of precipitation caused by ENSO.

Not the least of the accomplishments of TOGA has been the cooperation operation of two diverse research communities, the meteorological and the oceanographic communities, in pursuing common TOGA goals.

2

The GOALS Program and Its Scientific Objectives

This chapter presents the scientific rationale for the GOALS research program, enumerating and discussing the specific challenges that the program is expected to undertake, and then presents the scientific objectives of the program.

THE RATIONALE FOR GOALS

As successful as the TOGA program has been, its original goals have been realized only partially. TOGA was based on the assumption that variations in the tropical Pacific Ocean, specifically the warm and cold phases of ENSO, could be predicted without explicit reference to the rest of the world. Furthermore, it was assumed that prediction of the state of the upper ocean in this region, especially SST, could be used to infer seasonal-to-interannual climate variations in remote parts of the world on the basis of past correlations (see Figure 2-1). Predictions have been made as far as a year in advance using only initial wind data from the tropical Pacific. They have shown useful skill in predicting interannual variations in the tropical Pacific, specifically certain aspects of ENSO.

Connections to other tropical oceans have not been made despite tantalizing indications of precursors to ENSO arising over the Indian Ocean (Barnett, 1983) and indications that including the Indian Ocean in coupled models produced results different from those of Pacific-only models (Anderson and McCreary, 1985b). Understanding of the

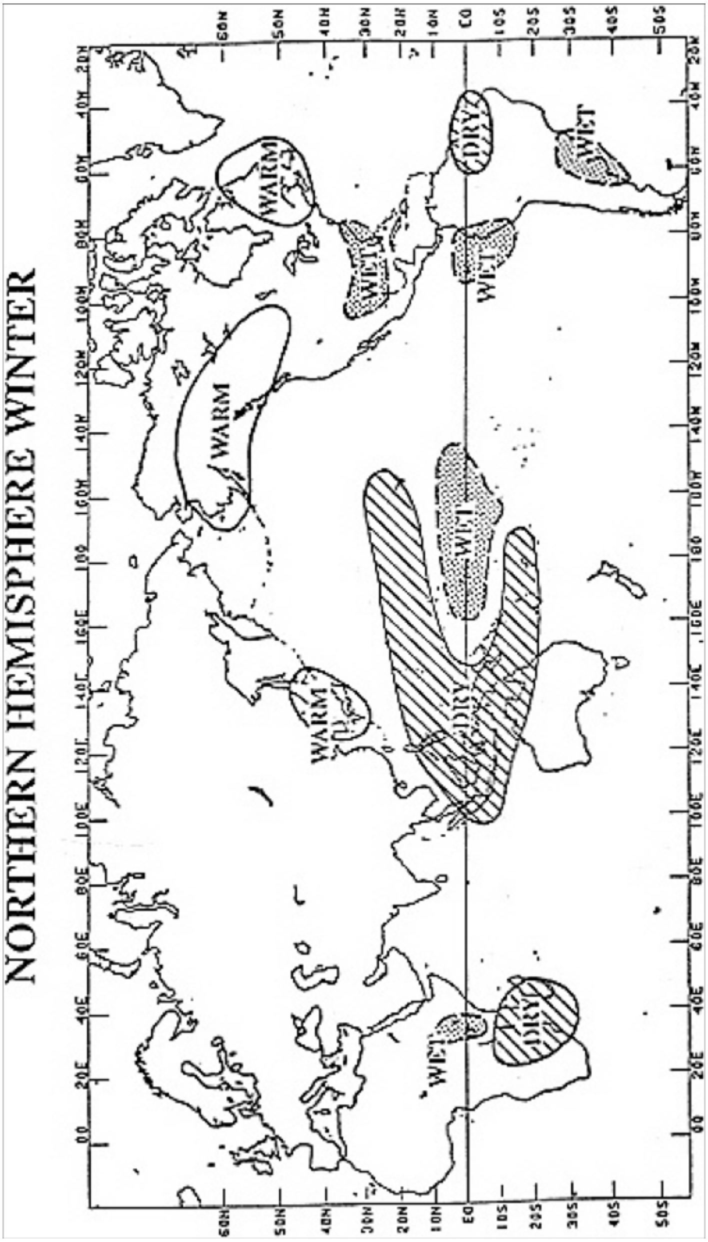

Figure 2-1 Schematic of large-scale climate anomalies associated with the warm phase of the Southern Oscillation during Northern Hemisphere winter. Based on Ropelewski and Halpert (1986, 1987) and Halpert and Ropelewski (1992).

connection of midlatitude atmospheric anomalies to tropical anomalies has thus far proven elusive. Furthermore, it has not yet been demonstrated how useful the ability to forecast tropical SST anomalies will be in predicting climate anomalies in midlatitudes. The Indian Ocean is connected with the tropical Pacific, and extratropical climate anomalies are correlated with extratropical SST anomalies, but these connections were not investigated by the TOGA program.

TOGA concentrated on understanding and predicting interannual variations in the tropical Pacific Ocean. Although no dynamical phenomenon of the climate system on seasonal-to-interannual time scales has been identified at middle and high latitudes comparable to ENSO, prospects for improving interannual climate prediction are likely to be enhanced with more accurate models of global upper-ocean and land-surface processes. The improved specification of the initial state of the global ocean–atmosphere–land climate system through the assimilation of new types of climate data will also likely enhance predictive capability.

TOGA helped develop skill in predicting aspects of ENSO, especially SST. This skill is seasonally dependent and varies according to the time of year of initialization. At certain times SST can be predicted well and at other times it is predicted poorly. The amount of global interannual variability that can be understood, simulated, and predicted is the focus of the GOALS program.

The GOALS program would endeavor to improve the existing predictive methods and would work to improve climate forecasts by including the effects of ocean areas beyond the tropical Pacific, non-ENSO related phenomena, and land-surface processes. It is expected that GOALS would accomplish several tasks:

1. The domain of interest would be extended from the tropical Pacific to the entire global tropics to understand seasonal-to-interannual tropical variability and to advance tropical predictive capability on time scales of months to a year or more. This would involve expanding the observing system to the other tropical oceans, using other programs to provide data for the land areas bounding these oceans, and using the combined data for better predictions over the global tropics.
2. Studies would be undertaken to improve understanding of the connections between the global tropics and higher latitudes for the purpose of defining the existence and extent of predictive skill. This would involve a comprehensive modeling program to develop an understanding

of the mutual interactions of the tropics and higher latitudes and the predictability of high latitude atmospheric anomalies.

3. GOALS would support CLIVAR research objectives in that program's attempt to observe and understand the mechanisms of global interannual variability, advance global predictability on seasonal-to-interannual time scales, and develop a capability for global prediction on these time scales. This would involve understanding the connections between global surface conditions (SST, land-surface properties, snow, and ice) and global atmospheric anomalies.
4. The original prediction goals of TOGA in and around the tropical Pacific would be more fully accomplished by developing improved coupled models and by exploiting the data produced by the TOGA observing system, especially the TAO array.

As the domain of the GOALS program expands from the original TOGA focus on interannual variability in and over the tropical Pacific Ocean to include global interannual variability, the range of processes considered would also need to expand. Expansion throughout the global tropics must involve consideration of interactions of the atmosphere with the land masses of India, Africa, and South America, as well as with the Indian and Atlantic oceans. Expansion into higher latitudes brings new considerations of the interactions with land and with the higher-latitude oceans, as well as with ice and snow changes over the land masses and in the high latitude oceans. The examination of the global ocean leads to opportunities to support and enhance the World Ocean Circulation Experiment (WOCE). Although GOALS would retain a focus on atmosphere–ocean interactions, the need to include land processes would also require close coordination and collaboration with other programs, especially with the Global Energy and Water Cycle Experiment (GEWEX), which is designed to improve the understanding of land-surface hydrology and other water-transport processes.

The modulation of the ocean–atmosphere coupling also has important effects on ocean biology and the exchange of carbon across the air–sea interface. The understanding of heat-flux fluctuations on seasonal-to-interannual time scales can provide useful input to ongoing programs such as the Joint Global Ocean Flux Study (JGOFS) and GEWEX for testing ideas about coupling among physical, chemical, and biological systems in the ocean, atmosphere, and on land.

The understanding of natural seasonal-to-interannual (i.e., relatively short-term) climate variability is an important prerequisite to detecting, understanding, and predicting anthropogenic climate change, especially greenhouse warming. Not only do short-term climate variations mask (or enhance) the effects of greenhouse changes, there is a distinct possibility that the slowly changing atmosphere and ocean may induce changes in the short-term climate variability that feed back on slow (for example, decadal) climate changes. Thus, the study of short-term climate variability is expected to make important contributions to the greenhouse problem.

As prediction models inevitably become more global in scope, a logical and needed extension of the TOGA prediction program is the investigation of the initialization and prediction of extratropical SST anomalies and their interaction with the global atmospheric flow. Knowledge of extratropical SST anomalies is of interest in its own right and may be necessary for understanding and predicting seasonal-to-interannual climate variations in midlatitudes.

Anomalies in soil moisture and snow cover have been shown to be important in the genesis and persistence of seasonal climate anomalies. Thus, to understand and predict climate variations, vegetation and land processes must also be considered, initially as boundary conditions and eventually as elements of a coupled system.

In summary, to understand and predict natural climate variations on time scales of seasons to several years, the state of the global upper ocean, atmosphere, and land system must be considered. Such a broad endeavor can be built from the current or anticipated TOGA prediction system in a sequence of measured and well-ordered steps. The study of the tropical Pacific Ocean should be expanded to include the tropical Atlantic, the Indian Ocean, and finally the global upper ocean. For time scales of less than several years, it is probable that only the upper few hundred meters of ocean and wind-driven ocean currents need be considered. Land-surface processes involving soil moisture and albedo need to be considered for observing and predicting the state of the land surface and its interaction with the climate system.

For all of these reasons, it is proposed that the GOALS program should now be launched, with the ultimate objective of observing, understanding, and predicting, to the limits feasible, total climate system variations on seasonal-to-interannual time scales. Useful predictions of climate anomalies on these time scales would have economic and social benefits that could be realized immediately. Droughts, floods, and variations in the monsoons are directly tied to ocean–

atmosphere interactions. Their prediction would result in significant human benefit.

SCIENTIFIC OBJECTIVES

The ultimate scientific objectives of the GOALS program would be to understand global climate variability on seasonal-to-interannual time scales; to determine the extent to which these variations are predictable; to develop the observational, theoretical, and computational means to predict these variations; and to make experimental predictions within the limits proven feasible.

The GOALS program would benefit greatly from the prior efforts of TOGA to establish an ENSO modeling and prediction capability and to establish the TOGA observing system. GOALS would develop a broader scientific scope than TOGA by extending the region of interest to the global climate system, by investigating the feasibility of predicting regional short-term climate variations throughout the world, and by expanding the observational and data transmissions network as appropriate to this investigation. GOALS also would investigate the influence of surface conditions of snow cover, soil moisture, and extratropical sea-surface temperature (SST) for describing or predicting interannual variations of regional climate and the feasibility of developing global ocean–atmosphere–land models for predicting these variations. The scientific objectives of GOALS are:

1. To observe, describe, and model the variability of the coupled global upper-ocean–atmosphere–land system on seasonal-to-interannual time scales, and to understand the mechanisms and processes underlying this variability and its predictability;
2. To improve the skill of predicting seasonal-to-interannual variations using coupled models of the global upper ocean–atmosphere–land system and to improve the requisite observing systems; and
3. To design and implement observing, computing, and data collection systems needed for describing and predicting the state of the global upper-ocean–atmosphere–land system.

These objectives would be met by a program of modeling, observing, process studies, and empirical studies. Ultimately, GOALS would seek to facilitate an orderly transition from an experimental to a permanent observing, computing, and data management system in sup port of regular and systematic seasonal-to-interannual climate prediction.

SCIENCE QUESTIONS

To accomplish the scientific objectives of GOALS, it would be necessary to answer many scientific questions. Following is a partial list of high-priority science questions for the GOALS program:

1. What are the structure and dynamics of the annual cycle of the coupled ocean–atmosphere–land system, and what are the reasons for its large spatial variability over the globe?
2. What is the nature of the global, interannual, climate variability and what is its relationship to the annual cycle? What processes give rise to such variability? Can our understanding of this variability be exploited for prediction?
3. What is the role of the slowly varying conditions at the earth's surface (SST, sea ice, snow cover, and soil moisture) in determining the nature of the interannual variations of the global atmosphere?
4. What determines low-level convergence of moisture in the tropics over water, land, and coasts? More generally, what determines the location of the thermal sources for the atmosphere?
5. What is the nature of tropical–extratropical interactions? In particular, what is the role of tropical SST anomalies in perturbing the extratropical atmosphere, and thereby generating extratropical SST anomalies? For what regions of the globe can accurate predictions of tropical SST anomalies be translated into skillful regional climate forecasts one or more seasons in advance?
6. What improvements in coupled ocean–atmosphere–land models are needed to represent convection, mixing, radiation–cloud–aerosol interactions, and the processes that determine the coupling of the atmosphere and ocean for the purpose of seasonal-to-interannual predictions?
7. Are there interactions between interannual and interdecadal variability? If so, what is the nature of these interactions? Are there similar or different mechanisms at work on these two time scales?
8. What is the role of synoptic fluctuations in the tropics and midlatitudes in seasonal-to-interannual climate variability and predictability?
9. What measurements of the global upper ocean and land surface are required to initialize the coupled models of the global ocean–atmosphere–land system for prediction of seasonal-to-interannual variations?

3

Large-Scale Interactions Among the Upper Ocean, Atmosphere, and Land

SPATIAL VARIABILITY

Tropics

It is generally accepted that the tropical atmosphere is primarily thermally driven by the latent heat released in deep convective clouds. A glance at any monthly or annually averaged precipitation chart (for example, Figure 3-1) indicates that these convective clouds tend to be clustered together in large agglomerations, which are referred to here as "heat sources."

There are three major localized heat sources: one is centered over the Amazon basin; one is over tropical Africa; and the largest one is over the "maritime continent," which comprises Indonesia, Malaysia, the surrounding islands, and adjacent oceanic regions. In addition to these localized heat sources, there are also the somewhat rectilinear-shaped sources characteristic of the Intertropical Convergence Zones (ITCZs) in each ocean, the northwest-to-southeast-oriented South Pacific Convergence Zone (SPCZ), and the similarly oriented South Atlantic Convergence Zone (SACZ).

The three major localized heat sources move seasonally, generally being most north and west in northern summer, and south and east in southern summer. The ITCZs are generally north of the equator, most northward in late northern fall and most equatorward in northern spring. The Amazon basin and African heat sources are

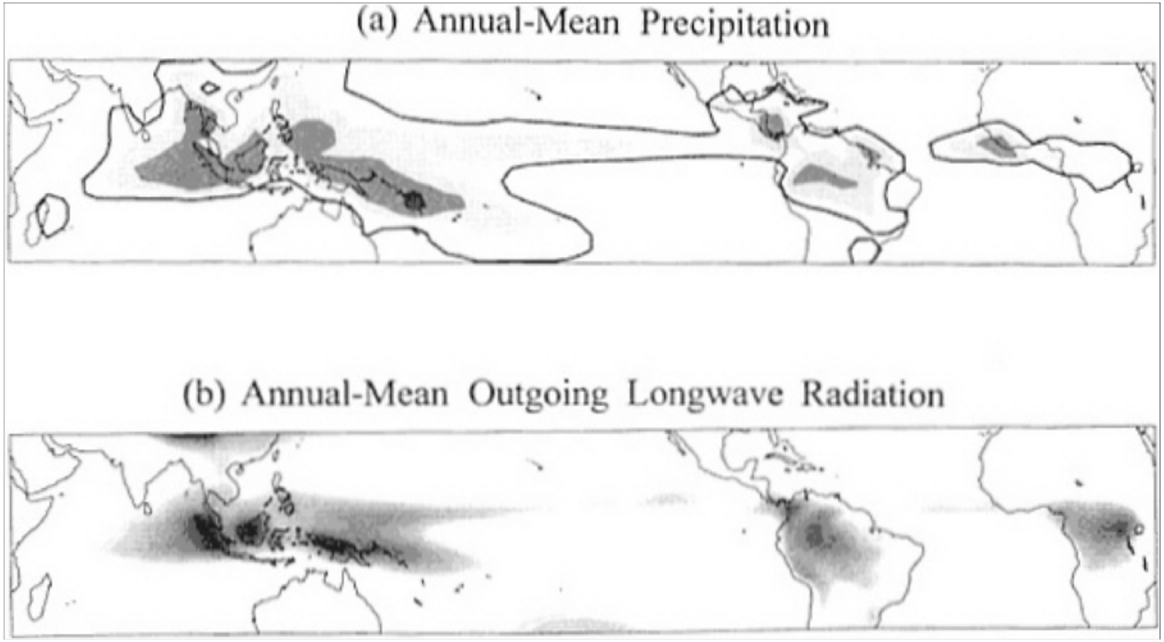

Figure 3-1 (a) Annual-mean precipitation over the tropics, after Jaeger (1976). The heavy contour encloses regions with amounts in excess of 12 cm per month; and light, intermediate, and dark shading correspond to amounts in excess of 16, 20, and 30 cm per month, respectively. (b) Annual-mean outgoing longwave radiation for the period 1974–1991. Values below 240 Wm^{-2}, indicated by the shading, are associated with regions of deep convective clouds.

primarily over land. The maritime-continent heat source responds strongly to SST changes. Indeed, it is the interannual motion of this heat source that can be identified with the ENSO phenomenon. During warm phases of ENSO, the maritime-continent heat source expands eastward into the anomalously warm tropical Pacific; during cold phases, it contracts back into the warm western Pacific. During a warm phase of ENSO, while the maritime-continent heat source is in its easternmost position, anomalously high rainfalls occur over the central Pacific and anomalously low rainfalls over Australia, Indonesia, and the Indian subcontinent. During the cold phases of ENSO, the opposite occurs.

It is known that the major heat sources interact. The problem of drought over the northeastern region of Brazil, for example, has features that have been correlated with the location of the ITCZ and SST anomalies in the Atlantic as well as the SST anomalies in the Pacific (Hastenrath, 1991, secs. 8.6 and 9.7). During the warm phases of ENSO in the Pacific, anomalies observed in the upper-level winds over the Atlantic can only be explained by anomalous modulations of the Amazon-basin heat source or long-range effects of the maritime-continent heat source. It is also known that the maritime-continent heat source is influenced by processes in and around the Indian Ocean as well as by SST changes in the tropical Pacific (Barnett, 1983, 1984a,b). The convergence of moisture into this maritime-continent heat source is partly due to the mean easterlies over the Pacific and partly due to the mean westerlies over the Indian Ocean.

The progress in understanding atmosphere-ocean interactions in the tropical Pacific can probably be attributed to:

1. The relative unimportance of land, which makes the maritime-continent heat source respond primarily to SST anomalies;
2. The tight coupling between SST and the regions of persistent precipitation over the Pacific (on monthly time scales the regions of persistent precipitation tend to follow the warmest water); and
3. The essentially linear nature of equatorial thermocline adjustment in the Pacific, making the problem of non-locally induced SST variability comparatively simple.

While the thermocline adjustment problem has similar dynamics in other tropical oceans, the tight relationship between heating and SST in the Pacific does not necessarily hold more generally. For example, April is the warmest month for SST in the northern Indian Ocean, but

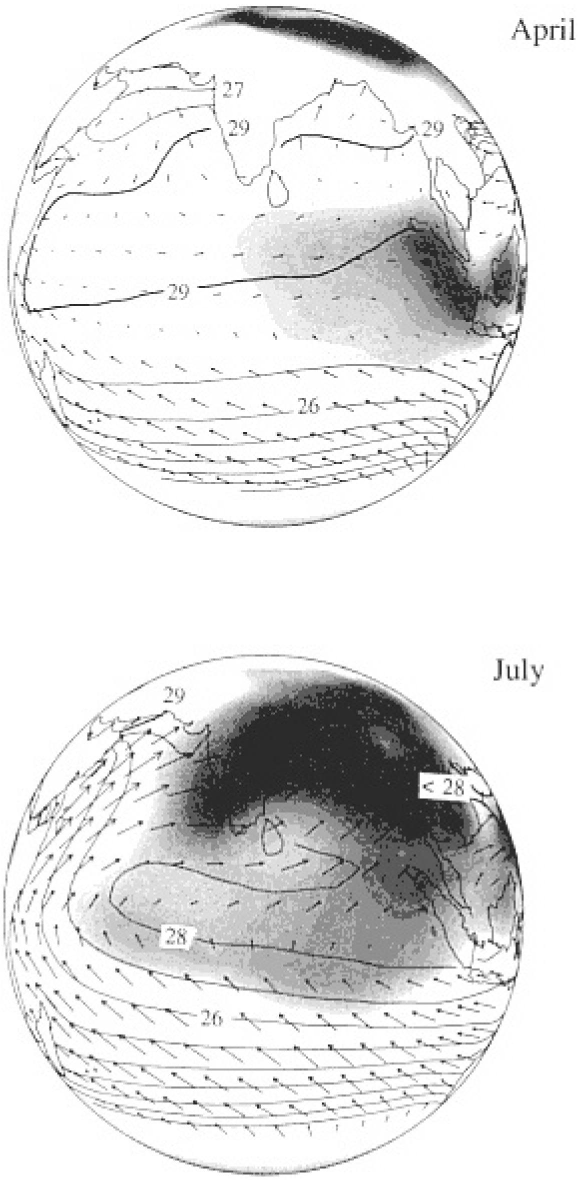

Figure 3-2 Climatological mean sea-surface temperature (SST), surface winds, and outgoing longwave radiation (OLR) over the Indian Ocean for the months of April and July. Contour interval of 1K for SST; OLR values below 240 Wm^{-2}, indicated by the shading, are associated with regions of enhanced deep convective clouds. SST and surface winds after Sadler et al. (1987).

it is not the time of maximum precipitation (see Figure 3-2). The time of maximum precipitation there is during the summer monsoons, when the northwest extension of the maritime-continent heat source lies over Southeast Asia and extends into the Bay of Bengal. There is clear influence of the land bordering the Indian Ocean during the northern summer (Webster, 1987). Indeed, the large amount of rainfall over the Indian subcontinent can be associated with the extension of the maritime-continent heat source into this region due to the effects of land. Thus, the motion of the maritime-continent heat source in the tropical Pacific due to SST variations in the tropical Pacific is only part of the puzzle. In general, climate variations in the tropics can be viewed as modulations and movements of the tropical heat sources, each affected by its underlying ocean, by combinations of ocean and land, or by land alone, and by interactions with other heat sources. To understand fully the motion and associated wind and precipitation patterns of the maritime-continent heat source, it is necessary to understand the influence of the conditions in and around the Indian Ocean on the convergence patterns of moisture, and to understand the interactions of the other heat sources with the maritime-continent heat source.

It is clear that thermal forcing in the tropics must be considered as a whole. In modeling the tropical thermal forcing, all the heat sources and sinks need to be included. The consequence of those heat sources that lie over the ocean (the maritime-continent heat source, ITCZs, SPCZ, and SACZ) will be determined primarily by atmosphere-ocean processes and will be directly affected by local evaporation, although modification will occur in some relation to their proximity to land. Over land (the Amazon Basin and African heat sources), the nature of the vegetation and soil moisture determine the local evaporation and surface temperature. It should be emphasized that when all the sources and sinks of tropical thermal forcing and their variability are taken into consideration, these land processes must also be considered.

Tropical-Extratropical Interactions

The interactions between the tropics and the extratropics occur over a wide range of spatial and temporal scales. It is believed that, in general, the tropics affect the midlatitudes on slower time scales (monthly or longer), while the midlatitudes influence the tropics on faster time scales (synoptic to monthly). On the "intermediate" time scale (a month or two), neither the tropics nor the extratropics dominates the mutual interaction. On these intermediate time scales the interac tions between the tropics and extratropics are the most complex, representing an interplay between the chaotic midlatitude flow and the more regular tropical flow (see, for example, N.-C. Lau et al., 1992; Molteni et al., 1993). There is clear evidence that tropical variations affect higher latitudes on interannual time scales (Horel and Wallace, 1981; Ropelewski and Halpert, 1987, 1989), but the mechanisms for this influence are still in question.

The Hadley circulation (the zonally averaged atmospheric meridional circulation) is driven by the zonally averaged tropical heating. It extends from inside the deep tropics all the way to the subtropics and is essentially responsible for the existence and maintenance of the subtropical jet (Schneider, 1977).

In addition to the midlatitude response of zonally symmetric heating in the tropics, teleconnection patterns forced by zonally asymmetric tropical heating sources are also an important source of midlatitude variability (Hoskins and Karoly, 1981; Branstator, 1985). The teleconnection pattern depends not only on the distribution of tropical heating but also on the three-dimensional distribution of the basic state climatological flow. Because the basic flow may be dependent on the tropical forcing and transients may play a role in the forced teleconnection patterns, the influence of the tropics on the midlatitudes may involve many different factors and may be very complex. In spite of these difficulties, the influence of the tropics on the midlatitudes has been demonstrated by numerical model experiments that show that the more realistic the simulation of tropical heat sources, the more realistic the simulation of midlatitude circulation.

The western boundary ocean currents (the Gulf Stream, for example) bring heat and salt from the tropics into midlatitudes and, as extensions of the boundary currents, into higher latitudes. Both the Hadley circulation and the western boundary currents can influence the middle and higher latitudes on time scales of seasons to a year or more. Eastern boundary Kelvin waves are also known to affect the higher latitudes on the time scales of interest to the GOALS program. For example, during warm phases of ENSO, the water off the western coast of the United States is usually warm and is a northward extension of the warm event taking place in the equatorial Pacific.

The influence of the midlatitudes on the tropics is most pronounced during the northern winter season and occurs on synoptic to intraseasonal time scales. The aggregate of these effects may significantly influence the evolution on longer time scales. One of the most noted examples of the midlatitudes influencing the tropics is the occurrence of cold surges associated with the Northern Hemisphere winter mon soon. Cold surges are midlatitude baroclinic disturbances that form over the east coast of China, over Japan, and in the East China Sea. They are often accompanied by strong surface northeasterlies that penetrate the equatorial regions. In addition, prolonged periods of high-frequency surface westerly wind fluctuations in the warm-pool region of the western Pacific have been linked, in part, to the excitation of equatorially trapped wave modes by lateral forcing from the extratropics—in particular, cold surges from the east Asian monsoon (K.-M. Lau et al., 1989). These westerly wind bursts and their accompanying rainfall are known to have significant impact on the salinity changes and, hence, on the dynamic and thermodynamic structure of the upper ocean on daily-to-weekly time scales.

The Extratropics

Due to large day-to-day atmospheric variability in the extratropics, possible influences of boundary forcings are difficult to discern in the winter season. However, variations in the land-surface conditions (soil moisture, vegetation, and so forth) can produce significant changes in the summer season's extratropical atmospheric circulation and monthly averaged temperatures over land (Shukla and Mintz, 1982; Manabe and Wetherald, 1987). The nature and degree of this interaction between the land surface and the atmosphere depend on the character of the dynamical circulation regime where land-surface changes are taking place. It is expected that the specification of initial land-surface conditions can lead to enhanced predictability during summer seasons. The land's influence depends on the interaction of the soil moisture and vegetation of the land surface with the overlying circulation. A sufficiently accurate treatment of atmosphere-land processes therefore provides a potential for prediction of seasonal mean temperatures, and possibly of rainfall, over continental midlatitude regions.

A large number of sensitivity studies using GCMs have shown that the simulation and prediction of the monthly and seasonal surface temperature and rainfall over land and those of the mean diurnal cycle are quite sensitive to the specification of the initial land moisture (Cook and Gnanadesikan, 1991; Fennessy and Shukla, 1992). Adequate initialization and assimilation procedures to specify the initial land-surface properties, including soil moisture and snow cover, and realistic parameterizations of energy and momentum exchanges between the land surface and atmosphere need to be developed for this potential predictability to be fully understood and utilized.

Finally, the question arises as to whether anomalies in midlatitude

SST on seasonal-to-interannual time scales affect the midlatitude atmosphere. Here the evidence is less conclusive. According to Wallace and Jiang (1987) and Wallace et al. (1990), there is no question about there being strong correlations between midlatitude SST anomalies and midlatitude atmospheric anomaly patterns. These papers point out that the simultaneous correlations between midlatitude atmospheric anomalies and midlatitude SST anomalies are even stronger than the simultaneous correlations between midlatitude atmospheric anomalies and tropical SST anomalies. The strong correlations are between the most dominant mode of SST variability and the most dominant mode of atmospheric variability for both the midlatitude Atlantic and the Pacific. The modeling studies of Lau and Nath (1990), using a 30-year record of observed global SST to force a low-resolution atmospheric GCM, found similar patterns of correlations.

For strong simultaneous correlations, one would naturally assume that there is a strong coupling between the midlatitude SSTs and the midlatitude atmosphere. The lag correlations indicate, however, that the correlation is much stronger when the atmosphere leads the ocean than when the ocean leads the atmosphere, indicating that in large part the atmosphere is forcing the ocean (Hasselmann, 1976). The existence of predictability of the coupled midlatitude atmosphere-ocean system needs to be much more intensively studied.

TEMPORAL VARIABILITY

Climate variability has been documented on all time scales, from a few tens of days to the age of our planet. The GOALS program would concentrate on the seasonal-to-interannual band. The following discussion concentrates on the temporal variability of climate and its relation to the seasonal-to-interannual band.

Subseasonal Variability

Short-term climate variability is often obscured by fluctuations on the subseasonal time scale. Of particular importance in this regard are the eastward-propagating planetary waves with periods on the order of 40 to 60 days, which modulate convection and perturb the surface wind field over the tropical Indian and western Pacific sectors (Madden and Julian, 1971). These planetary waves influence the timing of the onsets and cessations of the rainy seasons over much of Australasia, and they appear to be responsible for at least some of the well-defined breaks between extended episodes of monsoon rainfall. Their signature is evident in the thermal structure of the upper

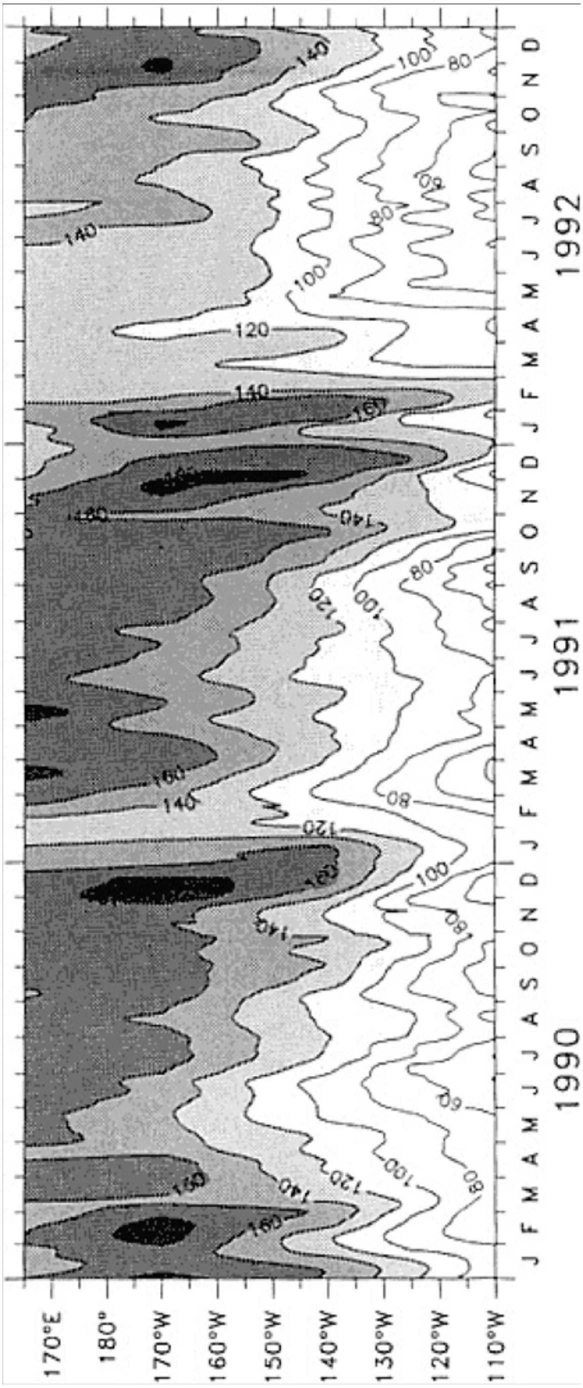

Figure 3-3 Time-longitude section showing the depth of the 20°C isotherm along the equator in the Pacific, based on data from the TOGA Tropical Atmosphere Ocean (TAO) array. Contour inverval, 20 m.

ocean all the way across the equatorial Pacific, as illustrated in Figure 3-3. At times it is difficult to determine whether large month-to-month changes in the various indicators of the state of the coupled tropical atmosphere-ocean system over the Pacific sector are signaling a major swing of the ENSO cycle or whether they are merely responding to the passage of one of these waves. It is conceivable that at certain critical junctures in the ENSO cycle, the passage of a wave might have important implications for the evolution of the coupled system over the course of the next few seasons. The extratropical circulation also exhibits large month-to-month variability which appears to be associated with teleconnections related to the 40-to-60-day wave (Weickmann et al., 1985) and the 20-day wave (Branstator, 1987; Kushnir, 1987).

Higher-frequency variability is also of interest in GOALS, to the extent that it mediates processes that determine the mean state and the evolution of short-term climate variability. In certain situations, analysis of the high-frequency variability can yield important insights into physical processes that operate across the full range of time scales. For example, Figure 3-4 shows time series of surface wind speed, insolation, and subsurface temperature at one of the TOGA TAO moorings over a 10-day period. It is evident that on the days when the winds were relatively strong, the diurnal cycle penetrated downward to at least 30 meters, with nearly neutral stratification during the nighttime hours. However, during the 3-day period of relatively weak winds, the diurnal cycle was confined to the topmost few meters; below 10 meters the water column was stratified throughout the 3-day period. By examining such sequences, it is possible to make inferences concerning the role of wind-driven entrainment in maintaining the nearly neutral stratification of the mixed layer and the time scale over which the ocean equilibrates to changes in the atmospheric forcing.

The diurnal cycle, which was evident in the preceding example, also plays a critical role in mediating vertical mixing and deep cumulus convection over land. Examples of other high-frequency phenomena of interest in GOALS are 20-to-30-day period tropical instability waves along the equatorial front in the eastern Pacific Ocean, which produce strong meridional transports of heat and zonal momentum; and 4-to-5-day period easterly waves in the atmosphere, which modulate the intensity of rainfall along the Atlantic and Pacific ITCZs.

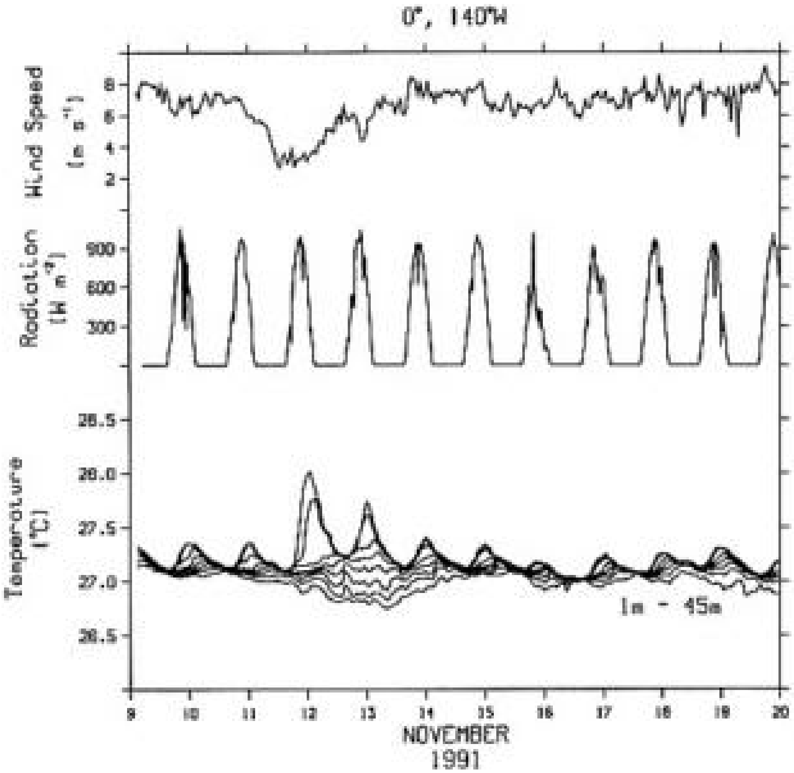

Figure 3-4 Time series of surface wind speed, insolation, and subsurface temperature at the TOGA TAO mooring on the equator at 140°W over an 11-day period. The subsurface time series are for depths of (proceeding from top to bottom) 1, 3, 10, 17, 24, 30, 36, and 45 m.

The Annual Cycle

The short-term variability that is the focus of GOALS occurs against a background signal of enormous importance, the annual cycle. An understanding of and ability to predict the interannual fluctuations that are of interest to GOALS depend on the ability to simulate and explain the annual cycle. The circulation changes associated with short-term climate variability represent relatively small distortions in the climatological mean annual cycle. For example, a modest shift in the wintertime planetary-wave configuration can bring below-normal temperatures and more frequent snowstorms to an area the size of the northeastern United States. A small displacement of the convection associated with the summer monsoon can bring floods or droughts to the semi-arid regions that lie along the margins of the monsoon rain belts. Subtle changes in summertime circulation patterns can also shift hurricane tracks. To predict the anomaly patterns as they evolve from one season to the next, it is necessary to understand and be able to model the annual cycle in the coupled ocean–atmosphere–land system.

Although the annual cycle is global, the processes that determine its character vary considerably from region to region. Therefore, a study of this cycle can conveniently be subdivided into components that focus on different regions. For example, the annual cycle of the eastern tropical Pacific is strikingly different from that of the Indian Ocean; each can be studied separately before turning to the links between them. The eastern tropical Pacific has a marked asymmetry relative to the equator; the warmest surface-waters and the mean position of the ITCZ are north of the equator. Interactions between the ocean and atmosphere are of prime importance in this region, and processes involving the land play a secondary role. In the Indian Ocean, on the other hand, the monsoons are strongly dependent on land processes.

The annual cycle has many other manifestations throughout the globe. In the equatorial Pacific, the cycle is more clearly evident in SST at the far eastern end, while it is evident in large monsoonal changes in winds and small changes in SST in the western warm-pool. Over all oceans it is manifested in the annual progression of SST, and over land in the annual progression of air temperature, sea-level pressure, vegetation amount, and soil moisture.

Gross features of the climatological mean annual cycle include, for example, the rainy seasons over the tropical continents that occur around the time of the equinoxes along the equator, shifting to midsummer as one moves away from the equator. Many such features can be understood as a direct response to the annual cycle in insolation, but some of the other features are no less difficult to explain than the ENSO cycle. For example, the observed meridional shifts in the ITCZs, which account for the single pronounced rainy season around March over much of equatorial South America, appear to be a consequence of complex interactions involving upwelling in the equatorial cold tongues, vertical mixing and evaporation, changes in the overlying stratus clouds, and changes in surface winds induced by the continental monsoons. Another example is the suddenness of the onsets of the climatological mean rainy seasons in some areas, which would be difficult to account for on the basis of the slowly varying insolation associated with the annual cycle. (See Table 3-1.)

TABLE 3-1 Climatological mean precipitation (in cm) for selected stations, showing the onset of the rainy season.

STATION		APR	MAY	JUNE	JULY	AUG	SEPT	OCT
Tucson	(32° N, 111° W)	0.8	0.4	0.6	6.1	5.4	3.4	2.2
Mazatlan	(23° N, 106° W)	0.1	0.2	3.4	16.3	20.1	21.6	6.5
Bombay	(19° N, 73° E)	0.0	1.8	60.1	93.5	61.3	34.4	10.4

The annual cycle modulates the amplitude, structure, and month-to-month persistence of temperature and circulation anomalies throughout the atmosphere and upper ocean, including those associated with the ENSO cycle. Pronounced seasonality is also evident in the predictability of these anomalies, as explained in more detail in Chapter 4. Indeed, it is difficult to conceive of a well-designed study of short-term climate variability that is not framed within the context of the annual cycle.

Interannual Variability

The ENSO cycle is the dominant mode of interannual variability in and over the tropical Pacific; understanding it and being able to predict it served as the focus of the TOGA program. It is now recognized that the ENSO cycle is due to interactions between the atmosphere and the upper ocean. The accompanying slow evolution of SST anomalies in the eastern Pacific is due to an atmosphere–ocean instability modulated by the effects of slowly propagating equatorial ocean waves and equilibrated by nonlinear processes in the atmosphere and ocean. ENSO manifests itself through the expansion of warm SSTs and heavy rainfall eastward into the Pacific, thereby modulating the annual cycle in the eastern part of the basin.

Throughout the ENSO cycle, there exist higher-frequency modulations due to short time-scale variability, particularly in convection, and due to 40-to-60-day waves. The ENSO cycle is in turn perhaps affected by longer time-scale processes, particularly in the ocean. The mean state of the upper ocean is dominated by the existence of a thermocline that is maintained by the slow (time scale on the order of hundreds of years) thermohaline circulation of the ocean.

Important interannual variability exists in other regions of the globe. In the Atlantic, the annual cycle dominates the SST variations, but small interannual changes in the location of the ITCZ affect the rainfall over northeast Brazil (Hastenrath and Heller, 1977). Over the North Pacific, strong interannual variability of SST and atmospheric circulation has been correlated with the ENSO cycle in the tropical Pacific (Horel and Wallace, 1981). Considerable interannual variability exists at midlatitudes in surface temperature, pressure, and precipitation (see, for example, Walsh and Mostek, 1980); in snow cover and soil moisture (for example, Walsh et al., 1985; Karl et al., 1993); and at higher latitudes in snowcover and sea ice (Chapman and Walsh, 1993). Over continents, soil moisture increases the time scale of atmospheric variability and leads to interannual variability of summer rainfall (Delworth and Manabe, 1989). Understanding this interannual variability and how much of it is predictable is one of the major objectives of GOALS.

Other manifestations of interannual variability include a tendency for phase locking between ENSO and the annual cycle resulting in an enhanced biennial variability (Rasmusson et al., 1990; Ropelewski et al., 1992), which shows up mainly as a biennially varying low-level circulation over the western Pacific and eastern Indian oceans. The possibility that the alternation of strong and weak Asian monsoons is related to interaction of the atmosphere with the surrounding oceanic regions is suggested by lag correlations between SST and monsoon rainfall (Yasunari, 1990). Observations of biennial variability of the Mindanao Current have been presented by Lukas (1988).

Decadal Variability

Interannual and interdecadal climate variations are not always clearly separable, even in retrospect, because of the absence of a spectral gap in the frequency domain. For example, warm episodes of the ENSO cycle are usually marked by cyclonic circulation anomalies over the central North Pacific, which induce negative SST anomalies in that region. Anomalies of that polarity were set up in association with the 1976–1977 warm episode, and they persisted throughout most of the 1980s. Warm wintertime surface air temperature anomalies downstream over western Canada that occurred in association with the same atmospheric teleconnection pattern contributed to the observed warmth of the Northern Hemisphere during the 1980s relative to the previous three decades (Trenberth, 1990; Trenberth and Hurrell, 1994). It is not clear whether this long-lived "regime shift" is rooted in the ENSO cycle itself or whether it is of extratropical origin (Trenberth, 1990). This example serves to illustrate how the assessment of interdecadal variability in the state of the climate system requires judgment as to whether the observed climate changes over the past few years should be interpreted as manifestations of interannual or longer-term variability.

A number of the important signals in the climate record exhibit variability on both interannual and interdecadal time scales. Examples include rainfall over areas such as the Sahel (Folland et al., 1986) and the U.S. Great Plains, hurricane and typhoon frequency and tracks, salinity anomalies over the North Atlantic (Dickson et al., 1988), and variations in sea-ice extent (Walsh and Johnson, 1979). Investigations of the interannual component of these signals, conducted within the context of the GOALS program, will contribute to the understanding of some of the processes that operate on longer time scales. Such processes include desertification, variability of the eastern and western boundary currents, the gyre circulations and their associated poleward heat fluxes, and relationships between the atmospheric circulation, sea-ice extent, salinity, and the production of bottom water in the marginal ice zones.

4

Elements and Growth of the Program

GOALS is envisioned as a 15-year program, running from 1995 to 2010. This period coincides with the lifetime of CLIVAR, the international program on climate variability and predictability being developed under the auspices of the WCRP.

ELEMENTS OF THE PROGRAM

Climate prediction on seasonal-to-interannual time scales is the focused objective of the GOALS program. In working toward this objective, GOALS would follow the successful example of TOGA by adopting these four major program elements:

- Modeling,
- Observations,
- Empirical studies, and
- Process studies.

Modeling that involves development and application of improved coupled ocean–atmosphere models for data assimilation and prediction is the unifying theme of the proposed GOALS program. Requirements of model initialization would help define the observational systems needed. Empirical studies would largely define the requirements of model improvement and would help evaluate which process studies are needed. These elements would provide the research framework for the development of operational climate monitoring and predictive systems.

PROGRAM GROWTH

The range of GOALS activities would expand as knowledge expanded. The following sequential ordering of developments in program growth represents a best guess as to the way knowledge will improve. This sequence is determined by the scientific considerations summarized in Chapters 2 and 3 of this report.

The GOALS program would proceed as a natural sequel to TOGA. It would concentrate initially on the ENSO phenomenon in the tropics. To improve skill in prediction, the interactions between the Indian Ocean (including the surrounding land masses) and the maritime-continent heat source would be examined. To exploit fully the predictability of the tropics, interactions with the Atlantic and its bordering South American and African land masses would next be considered. As the area of investigation expanded eastward over Africa, the interactions with the African land mass would have to be examined, and the observed decadal variations of rain in the Sahel would become of interest. The effect of the global tropics on the higher-latitude atmospheric circulation would become the next challenge. Finally, GOALS would examine the effects of higher-latitude ocean, land, and ice on seasonal-to-interannual climate predictability.

As sound as the preceding outline of expected program growth may be, it is possible that flexible program management and continuous, routine assessment of program directions and achievements could result in adjustment to the ordering. For example, models are generally run in a global mode, and modeling breakthroughs can suggest new avenues of research. It may be possible to identify those qualities of the mean state that enhance or degrade the ability of anomalies to propagate out of the tropics into higher latitudes (see, for example, Trenberth and Branstator, 1992). If so, this would point to features of the mean state that must be measured and modeled correctly, and a major advance in midlatitude prediction could ensue.

The rest of this chapter discusses the four program elements listed above. A section on each describes the expected contribution of that component to the overall program, together with the challenges and objectives in that particular area.

MODELING

The overall strategy for the GOALS modeling component is to work within the framework of the existing WCRP programs on climate modeling and to build on the success of the TOGA program. The observational and process study elements of GOALS would, of necessity, be regional and would expand initially from the TOGA region of focus—the tropical Pacific—to the global tropics. The modeling component of GOALS would include a hierarchy of models but would emphasize large spatial scale. Atmospheric GCMs are global by nature, and the coupling of the atmosphere to the ocean and land would be with GCMs that are also global in extent. Therefore, many of the extensions, problems, and areas of uncertainty that GOALS would eventually face might first be encountered in a modeling context. From this point of view, interannual predictions would be global in scope before the initialization data were available for the global ocean and global land. The modeling component of GOALS therefore emphasizes the extension of coupled models of the tropical ocean and atmosphere to include the tropical land and extratropical atmosphere and upper ocean, and simulation of soil moisture, snow, sea ice, and vegetation.

The deep ocean may be important to understanding climate variability on time scales of a decade or longer, but a working hypothesis for GOALS is that this complexity is not crucial to extending the range of short-term climate prediction. More important is the specification of the initial condition of upper-ocean, sea-ice, and land-surface properties that potentially have memories of a season or longer. Also necessary is the development of coupled models that are comprehensive, but balanced in terms of the complexity with which key atmospheric, oceanic, and land processes are represented.

It is important to develop coupled ocean–atmosphere–land models that exhibit the full range of variability, not only on the annual scale but also interannually. To verify the spectrum of variability, coupled models must be executed for about 30 model years so that the annual cycle is well-defined. The interannual variations with respect to this annual cycle can then be isolated. Evaluation of the modeled annual cycle thus requires a good annual climatology of important atmospheric, land, and oceanic quantities. This climatology must include global SST, land wetness, and surface wind stress as primary quantities; as well as global boundary-layer depths in the atmosphere and ocean; sea-level pressure; upper-level horizontal fluxes of heat, momentum, and moisture in the atmosphere; and fluxes of heat and fresh water in the ocean. The preparation of a global land wetness climatology, which is needed for running and verifying climate models, would require close cooperation with the ongoing Global Energy and Water Cycle Experiment (GEWEX) program.

Atmosphere–Ocean Coupling

The success of coupling the atmosphere to the ocean depends on correctly predicting the surface quantities: SST and surface fluxes of heat, fresh water, and momentum. The determination of these quantities requires much more than a correct parameterization of boundary-layer processes, as these quantities are sensitive to many atmospheric processes above the boundary layer, such as convection, radiation, and cloud formation. Clouds influence the surface radiation budget and enhance sensible heat flux, evaporation, and the surface wind stress in the vicinity of deep convection (Johnson and Nicholls, 1983). Clearly the development and evaluation of atmosphere and ocean models for use in coupled models will require long, accurate records of global SST and wind stress.

The coupling of atmospheric GCMs to land-process models and to oceanic GCMs is a large and challenging undertaking, but one that is ultimately foreseen as offering the best hope for producing skillful forecasts of seasonal-to-interannual climate variations. The development of coupled GCMs has been slowed by the difficulty of simulating the correct spectrum of variability. This problem is gradually being overcome; several coupled GCMs now show reasonable annual and interannual variability. Essential to all these efforts is the correct modeling of the climatology—particularly the annual cycle.

The annual cycle, forced by annually varying solar radiation, is not adequately simulated in the present generation of fully-coupled atmosphere–ocean models. Successful simulation of the annual cycle is therefore not only a validation of a coupled model, but a prerequisite for correctly simulating interannual variations. Nevertheless, because of its large amplitude and regularity, the annual cycle is relatively well observed and well documented. Some of its more robust features, such as the northern hemisphere winter planetary-wave configuration, are well-simulated in the present generation of atmospheric general circulation models and coupled models, although others are not. For example, the models have difficulty reproducing both the sharpness and subtle seasonal changes in the convergence zones over the tropical South Pacific and South Atlantic as well as the precise timing of the onset and cessation of the climatological mean rainy seasons in some areas. Some of the systematic biases in the models are larger than the anomalies associated with short-term climate variability. More accurate representation of the physics in the models will be needed to correct these deficiencies in the simulated annual cycle.

In tropical latitudes, annual SST variations occur as a result of the annual variation of both wind stresses and heat fluxes accompanied by both mixing and advection in the near-surface ocean. At higher latitudes, heat and momentum fluxes through the ocean surface are accompanied mainly by mixed-layer processes, while advection in the ocean is relatively unimportant (Gill and Niiler, 1973), at least away from coastal boundary current regions. Since cloud and humidity variations in the atmosphere affect the heat fluxes into the ocean, the problem of annual and longer-term SST variability in the ocean is fundamentally coupled to atmospheric variability. Since the cloud and atmospheric variability is partly forced by SST variability, the modeling problem is truly coupled.

Existing coupled GCMs have proven capable of modeling the ENSO phenomenon with varying degrees of success (for example, N.-C. Lau et al., 1992; Philander et al., 1992). Recent models have even been able to simulate both the annual cycle and the ENSO cycle (Nagai et al., 1992; Latif et al., 1993a); but, to date, no coupled GCM has been capable of correctly simulating the entire annual and interannual spectrum of variability. The status of coupled atmosphere–ocean models and their success in simulating the observed climatology, both annual and interannual, is reviewed by Neelin et al. (1992) and is discussed in the context of prediction in Appendix A of this report. One of the objectives of GOALS would be to continue improving coupled ocean–atmosphere–land general circulation models with a view toward correctly simulating the spectrum of climate variability.

Future modeling of the coupled atmosphere–ocean models must come to terms with properly defining criteria for successful coupling. These criteria will need to be defined both for the surface atmospheric and oceanic fields so that an atmospheric model that satisfies its own criteria, when coupled to an ocean model that satisfies its own criteria, will produce a coupled model with correct behavior. Until this is possible, the essence of coupled models will not truly be understood.

Atmosphere–Land Coupling

Changes in the land-surface properties of albedo, surface roughness, and soil moisture produce changes in ground temperature, evaporation, and sensible heat flux. Changes in horizontal gradients of ground temperature produce changes in the convergence of moisture. Changes in vertical gradients of temperature in the presence of moisture convergence produce changes in convection and rainfall, which subsequently further alter the soil moisture. The nature and degree of these interactions depend on the character of the dynamical circulation regime in which the land-surface changes are taking place. The occurrence of prolonged droughts in subtropical regions (where subsidence occurs) and even the tendency of heat waves to persist in the extratropical regions can be explained, at least in part, by atmosphere—land interactions (Atlas et al., 1993). An accurate treatment of those atmosphere–land interactions provides potential for prediction of seasonal mean surface temperature and possibly rainfall over the continental United States.

The development of realistic models of coupled ocean–land–atmosphere systems for prediction of short-term climate variations will require comprehensive land-surface process models that predict soil moisture, land-surface albedo, snow pack, and surface roughness, rather than prescribe them. Since the task of developing better land-surface models and preparation of data sets to validate land-surface models rests primarily with GEWEX, GOALS intends to take advantage of a successful GEWEX program to help incorporate the role of the land surface into global ocean–atmosphere–land models suitable for examining climate variability.

Experimental Prediction

The ultimate test of a program focusing on seasonal-to-interannual variability is the ability to predict variations. The development and evaluation of coupled upper ocean–atmosphere–land and cryosphere models, the development of a data collection and assimilation system, and a set of hindcasts for predictive validations are all required for the development of improved predictive capability. Sufficient data for proper model initialization and evaluation are crucial to the enterprise.

Advances in prediction with coupled upper ocean–atmosphere–land models is heavily dependent on computational infrastructure. Access to the needed computer resources and the concomitant data storage, high-speed data transmission, and visualization facilities needs to be improved, and simulation and evaluation standards need to be developed. Such standards should include model documentation, simulation and intercomparison tests, standard formats for the exchange of model data, and visualization protocols.

The best way of accomplishing the prediction objectives of GOALS is by establishing the needed computational infrastructure, by maintaining a strong and expanded research program focused on developing and making predictions (for example, by continuing the TOGA Program on Prediction [T-POP] into the GOALS era), and by a strong proposal-based research program investigating the model questions involving simulation and predictability on short climatic time scales.

It is anticipated that GOALS would interact strongly with regular and systematic short-term climate prediction activities such as the proposed International Research Institute for Climate Prediction (IRICP) (Moura, 1992), the Coupled Modeling Project at the National Meteorological Center, and other similar activities.

OBSERVATIONS

GOALS requires observations (1) to increase understanding of processes not well parameterized in large-scale models; (2) to use for assessment and prediction, including initialization of forecast-analysis systems; (3) to provide the research foundation for operational monitoring; and (4) to provide ground-truth for satellite data products. The current TOGA observing system forms a nucleus for GOALS, which requires observations of the seasonal-to-interannual variability of the global upper-ocean circulation. The following sections are provided to help guide the future development of a global observing system; they do not fully specify such a system. A detailed implementation strategy must still be developed.

Observations Over and In the Ocean

The present TOGA ocean observing system forms a nucleus for development of a GOALS observing system to monitor variability on and in the tropical Pacific (NRC, 1994). Key parts of the TOGA observing system have only recently been fully established; their predictive benefits would be realized during GOALS. The emerging Global Ocean Observing System (GOOS) program will be crucial to making the long-term ocean observations needed by GOALS and will be essential for providing observations to operational government agencies.

The TOGA TAO array, which measures surface winds and upper-ocean thermal structure in real-time in the equatorial zone, will not be fully established until the very end of TOGA in 1994. In addition to the TAO array, TOGA measurements of upper-ocean thermal structure, including SST, derive from a variety of sources: VOS XBTs (volunteer observing ships expendable bathythermographs), VOS surface data, drifters, and satellite retrievals. TOPEX/Poseidon provides data on sea-surface height variations and in tropical areas these data can provide the basis for an estimate of thermocline depth variations. The various techniques have different strengths, and some have dual applications. Over the next several years, a heterogeneous array of satellite sensors for SST will be flown. These include AVHRR

(Advanced Very High Resolution Radiometer), ATSR (Along Track Scanning Radiometer), MODIS-N (Moderate Imaging Spectrum-Nadir), and OCTS (Ocean Color and Temperature Scanner). Considerable new work will be required to learn how to produce and calibrate SST products to a known, climatically useful accuracy.

TOGA has supported the development and deployment of radar-based atmospheric sounding systems at several sites across the tropical Pacific. Preliminary analyses of these data indicate they are likely to be important for GOALS. The wind-profiling radar at Christmas Island has identified serious problems in the way boundary-layer wind shear is analyzed in an operational forecasting model. Automated, integrated sounding systems formed the core of the soundings array in TOGA-COARE. Systems like these offer promise for filling key gaps in the operational sounding network across the global tropics.

Current knowledge of seasonal-to-interannual variations of global upper-ocean circulation is poor. One of the measures of success of the GOALS program would be obtaining new results with respect to the seasonal-to-interannual variability of global upper-ocean circulation and its contribution to atmospheric variability. Knowledge of the seasonally varying upper-ocean circulation is important to evaluate results of the GOALS models. The optimum mixture of in situ and satellite observations to describe upper-ocean circulation variability must be determined. Altimeter and scatterometer data may need particular attention because of their potential utility in providing information on the upper ocean. In addition to thermal and flow measurements, accurate surface and subsurface salinity measurements should be obtained. Salinity measurements may provide the best opportunity to evaluate the hydrologic cycle in coupled models. Precipitation over the ocean is an important, but poorly sampled, quantity. Various techniques have been developed to measure precipitation and should be tested at sea. Autonomous ocean profilers of temperature, salinity, and current offer potential for extended time series in remote regions at a considerably lower cost than present systems.

The penetration of visible irradiance to depths below the upper layer of the ocean has a potentially large influence on the evolution of SST. Observations of the ocean color field from satellites and from in situ measurements, in conjunction with high-quality surface irradiance fluxes, would be useful to evaluate this potentially important energy source in the mixed-layer heat budget.

Observations Over Land

The existing system of climate-related measurements, especially upper-air measurements, is in a state of decline. From 1989 through 1992, reports to the National Meteorological Center (NMC) from upper-air stations in tropical Africa decreased by 50 percent. In the United States and at overseas military stations, serious consideration has been given to reducing the frequency of upper-air observations. Automated Aircraft Enroute Reports (AIREPs) have increased along air routes near the requisite ground equipment, but there has been a decrease in the frequency of manual reporting from remote routes. Automated sounding equipment should be considered as a way of improving the situation, particularly in the tropics, where strong land–atmosphere interactions give rise to a substantial part of the long-term predictability of the coupled system.

In addition to the technological challenges for increasing meteorological observations in data-sparse regions, free and open scientific data exchange is being questioned in several countries. In recent years pressures have increased on many national weather services to recover the cost of their investments in observing systems. As a result, some countries have abandoned the standard practice of exchanging data for scientific research at the minimal cost of reproduction. If this trend continues, it would threaten the success of the GOALS project as data became too costly for investigators to purchase.

The decline of the World Weather Watch (WWW) radiosonde network across the global tropics is of particular concern, considering the emphasis in GOALS on predictions of regional atmospheric variations. Boundary-layer processes in particular must be understood and accurately modeled to achieve GOALS objectives pertaining to climate fluctuations of moisture convergence and precipitation. Observations of winds, temperature, and humidity above the land surface would be much more important for the success of GOALS than they were for the more limited objectives of TOGA.

Land-surface models usually recognize several land-surface types that differ in vegetation structure and physiology, and several soil types that differ in hydrologic properties and albedos. GEWEX will be concerned with the development and analysis of these data sets and of additional data to evaluate land-surface models. However, GOALS would require the accurate initialization of some components of land-surface models (for example, soil moisture).

Satellite Observations Over Land and Ocean

Remote sensing plays a critical role in providing the global data sets required to initialize, force, and evaluate models for GOALS. The GOALS time period, 1995–2010, coincides with a coordinated increase in earth-observing satellites scheduled by the National Aeronautics and Space Administration (NASA), European Space Agency (ESA), Centre National d'Etudes Spatiales (CNES), and National Space Development Agency of Japan (NASDA). Multisensor spaceborne platforms (such as NASA's Earth Observing System [EOS], Tropical Rainfall Measurement Mission [TRMM], ESA Envisats, and NASDA ADEOS) will provide unprecedented coverage of atmosphere, ocean, cryosphere, and land variability. For example, there will be radar scatterometer measurements to derive ocean-surface wind velocity; radar altimeter observations of sea-surface topography; radar measurements of tropical rainfall; passive microwave observations of sea-surface wind speed, sea ice, snow cover, and water vapor; and high-resolution spectrometer/radiometer estimates of SST, albedo, cloud fraction, surface irradiance, vegetation, and ocean color (see Table 4-1). There would be a need to keep abreast of developing technologies that have potential for the remote sensing of soil moisture and sea-surface salinity. GOALS requirements would assist in defining the spatial and temporal requirements for such quantities.

GOALS must not become dependent on proposed remote sensing missions because, historically, delays or changes in missions have often resulted in missed opportunities for scheduled research pro

TABLE 4-1 Satellite Data Products for GOALS

DATA PRODUCT	SATELLITE PLATFORM AND/OR SENSOR
Atmospheric Temperature Profile	MSU, AIRS
Clouds	AVHRR, VISSR
Land–Atmosphere Flux	SAR
Phytoplankton Abundance	SeaWiFS, OCTS
Precipitation	TRMM
Sea-Ice Extent	SSMI
Sea-Surface Height	ERS-1, TOPEX/Poseidon, ERS-2, GFO, TPFO
Sea-Surface Temperature	AVHRR, ATSR, OCTS
Snow Cover	SSMI, MODIS-N
Surface-Wind Speed	SSMI, ERS-1, TOPEX/Poseidon, ERS-2, GFO, TPFO
Surface-Wind Vector	ERS-1, ERS-2, NSCAT, Seawinds
Vegetation	AVHRR
Water Vapor	SSMI

grams. However, the successful implementation of the currently planned earth-observing satellites (TRMM, EOS, Envisats, and ADEOS) would greatly assist the accomplishment of the objectives of GOALS. GOALS would take full advantage of these remote sensing missions when sustainable and verifiable data were obtained and were suitable for process and modeling studies on seasonal-to-interannual time scales. The ultimate suitability of the remote sensing data would depend critically on rigorous analyses, reanalyses, and continuous verification with corresponding in situ data. Continuity and calibration of satellite measurements throughout the GOALS program would be very important and should be achieved by planning for brief intervals of overlap between aging and replacement spacecraft and by planning for a well-maintained, in situ observational network.

Expansions and Extensions

Expansion of the observing network would be an important part of the GOALS program. The critical role of surface-wind forcing in the tropical ocean and the substantially different model outputs that arise from different tropical surface-wind products have driven the development of the TAO array in the Pacific. TOGA TAO is the only feasible near-term means for obtaining data for accurate, spatially well-mapped winds in this region. Many of the same dynamical considerations and sampling arguments that were used to advocate TAO in the Pacific also apply in the Indian and the Atlantic oceans. It is important to extend TAO measurements into the equatorial zones of these two oceans.

If indeed an accurate (to within 0.2K to 0.3K) global mapping of SST is required for significant advances in extratropical climate predictions, then there is much observational work to do. Satellite retrievals alone cannot yield the desired accuracy; a substantial increase in "sea truth" measurements with which to calibrate satellite data will be needed. Development of an optimum mixture of techniques and optimum sampling schemes will be a complex task.

Technical developments should be pursued to enhance and extend global observations. It is clear that the capability represented by the VOS fleet is not being used to full advantage. Efforts to design and deploy robust packages capable of accurate measurements and of accurate reporting via satellite should be encouraged. The primary beneficial impact would be on standard surface meteorological observations (such as sea-level pressure, SST, and so on), but the possibility of adding streams of other valuable data (such as salinity and air-sea fluxes of heat and water) should be taken into account.

Carefully developed subsurface observations in midlatitude oceans will be useful in understanding and possibly predicting global climate variations.

GOALS science objectives require greatly enhanced monitoring of the atmosphere above the ocean surface to characterize and understand boundary-layer processes such as moisture convergence and vertical fluxes of momentum and heat. At present, there are no long-term time series of boundary-layer profiles for these variables over the ocean that can be used to evaluate and improve atmospheric models. Therefore, deployment of cost-effective systems capable of making such measurements would be useful. With the development of unmanned land-based profilers and stabilized shipboard profilers, several of the key technological obstacles to deploying sounding systems on buoys have been overcome.

For data transmission, GOALS must rely, at least in its early years, on the Global Telecommunication System (GTS) for the transmission of standard meteorological data in real-time. The limitations of the GTS are well known. The program must also rely to a large extent on the Argos system platforms for transmission of GOALS-specific data. Actions have been taken to modernize and increase the efficiency of the Argos system and its capacity to handle a future increase in the numbers of platforms and in data rates. A continuing problem, however, is the charging mechanism for the Argos system. Regular upgrading of the technical capability of Argos and the examination (by the National Oceanographic and Atmospheric Administration [NOAA] and CNES) of possible different charging mechanisms should be encouraged. At the same time, GOALS should also be ready to exploit new technological developments, which might conceivably offer more efficient operational services in the long term.

EMPIRICAL STUDIES

Empirical diagnostic studies of observational data would be carried out in conjunction with the other elements in the GOALS program. Some of these studies would be exploratory in nature. Some would capitalize on new components of the observing system, while others would rely on long records of historical or paleoclimatic data. In some cases, the observational results would be compared with results based on model simulations. Results of such empirical studies would be of interest in their own right, but they also would provide motivation for numerical modeling experiments and would serve as justification for process studies. Empirical studies could also point toward needed new components of the observing systems.

Scientists participating in GOALS would have access to a number of valuable new data sets. With the availability of comprehensive data sets, there can be more comprehensive diagnostic studies of processes, circulation statistics, and budgets of heat, momentum, mass, and moisture. Improved estimates of atmosphere–ocean and/or land-surface–atmosphere exchanges should be possible. In addition, empirical studies of observed relationships are invaluable for providing insights and delineating phenomena that need to be modeled and understood.

Reanalysis projects carried out at the National Center for Atmospheric Research, NMC, and other operational numerical weather prediction centers promise to provide greatly improved, global, gridded data sets for empirical studies of short-term climate variability (Kalnay and Jenne, 1991). These reanalyzed data sets will extend further back into the past than currently available data sets of this type do, and they will be much more reliable, particularly in the tropics. Significant improvements are expected for the irrotational component of the wind, which is of critical importance for diagnosing variations in the intensity and structure of the tropical heat sources. Assuming that modeling and data assimilation continue to improve, it will be desirable to repeat this process at regular intervals to improve and lengthen the data sets.

One of the significant accomplishments of TOGA has been the development of an operational tropical-ocean data-assimilation effort (Leetmaa and Ji, 1989). The first gridded ocean data sets derived from this effort recently became available to researchers. During GOALS, similar activity would expand to encompass the global ocean, the land surface, and the cryosphere. Another important development that has taken place during the TOGA period has been the increasing availability of climate data in near real-time through monthly publications and by on-line data services provided by various government agencies. It is important that these agencies continue to develop this infrastructure so that the scientific community will be able to respond to the increasing pressures for real-time assessments of the status of ENSO and regional climate anomalies throughout the world.

Gridded satellite data sets are playing an increasingly important role in research on short-term climate variability. NASA's "Pathfinder" project offers the hope of reanalyzed versions of some of the more important, older, satellite data sets. It would be important that GOALS scientists be involved in the planning of these projects so that the resulting data sets would be available in formats suitable for the study of short-term climate variability. In a similar manner, GOALS scientists would have an interest in the maintenance and upgrading of data sets from ocean-based and land-based measurements such as the Comprehensive Ocean-Atmosphere Data Set (COADS) and the archive of XBT data. Hence, it is important that the implementation plan for data management in GOALS include provisions, not only for the observations taken as part of the program, but also for the maintenance and upgrading of the historical data sets that are needed for empirical studies.

Questions of midlatitude variability, correlations of SST variations with atmospheric variations, effects of mean flows on tropical–extratropical interactions, and variability of the Hadley Cell have been and can be approached further by analyses of both existing data and future data as they become available. An intensive study of the COARE data set should also be undertaken. The COARE program acquired an enormous amount of data concerning the interaction between the western Pacific and the overlying atmosphere during COARE's intensive operation period (November 1992 to February 1993). These data sets will have information important to the GOALS program, and it is both prudent and necessary that GOALS exploit existing data sets fully for use in planning future process study experiments. It will undoubtedly take many years past the formal end of TOGA to fully exploit the COARE data set.

To support empirical studies of the climatological annual cycle and seasonal-to-interannual variability (40-to-60-day oscillations, quasi-biennial oscillations, and so on), GOALS would assemble and analyze a 30-year (1971–2000) climatic data set. Central to this effort would be the development of techniques for assimilating heterogeneous and sparse data into coupled models of the atmosphere, upper ocean, and land. In addition to examinations of the exchanges of energy, momentum, and water between the various components of the climate system, special emphasis would be placed on the determination of upper-ocean circulation and density structure; rates of change of the internal atmospheric structure due to water phase change and radiative heating; the spatial distribution of soil moisture, snow and ice; and measures of the distribution and properties of vegetation.

PROCESS STUDIES

The objective of GOALS process research is the improvement of the observations and understanding of the climatically important processes that are poorly modeled or parameterized in the models used to predict short-term climate variations. Process studies conducted in the field would provide research-quality data sets for detailed diagnosis of the most serious deficiencies in the models. These data sets would also be available to improve parameterization schemes designed to remedy these deficiencies in the models. Process studies should exploit the combination of numerical models and new observations in a synergistic and efficient manner. Because additional observations will be needed to make progress in this area, process research would guide the development and expansion of the emerging global climate observing system and would therefore also contribute to planning the observational component of GOALS.

If more process studies were proposed than could be conducted, the primary scientific considerations guiding the selection process would be the likelihood that a proposed study would (1) make an important contribution to advancing the state of the art of modeling, especially insofar as it influences short-term climate prediction, and/or (2) elucidate the processes that govern the behavior of the coupled atmosphere-ocean system. Logistical considerations such as the feasibility of conducting operations in various proposed sites, the ability of more than one group of investigators to effectively share the same observing platforms, and the prospects for cost sharing with other nations would also inevitably play a role in the selection process.

Following are some potential candidates for process studies, grouped by latitude belt.

- Process studies in the tropics could examine: oceanic heat balance in regions where the models have difficulty simulating SST; maintenance of the oceanic mixed layer in the presence of equatorial upwelling; the reflection of Rossby waves off the western boundary and related flow through the straits surrounding Indonesia; parameterization of the strong backing of the wind with height in the planetary boundary layer, which is not well-simulated in current numerical weather-prediction models; the role of the stratus cloud decks in the oceanic heat balance; the role of the western boundary currents in the oceanic heat balance and the transport of heat to higher latitudes; and atmosphere–ocean interaction in association with the 40-to-60-day waves.
- Process studies in the higher latitudes could examine: the roles of coastally trapped Kelvin waves and coastal current systems in accounting for the effects of ENSO along the coasts of Mexico, California and Chile; the processes that modulate the production of subtropical-mode water

in the Sargasso sea and to the north of New Zealand, and the associated overturning circulations; the origin of subpolar salinity anomalies and their role in modulating sea–air energy fluxes; and the causes of interannual variations in sea-ice extent and their feedback on the atmosphere.

The precise form of the process studies (or field programs consisting of regional sets of process studies) that would be performed as part of GOALS cannot be specified more precisely at this time. It would depend on many things, including results of the COARE experiment, progress in coupled atmosphere–ocean modeling, results of empirical studies of tropical and midlatitude variability, possibilities of logistical support, funding, and international cooperation. Before process studies for GOALS got under way, it would be important to hold a series of implementation meetings during which the shape of process research and its interaction with the rest of the GOALS program could be better defined.

CONSORTIA AND PRINCIPAL INVESTIGATOR GROUPS

The four elements of GOALS—modeling, observations, empirical studies, and process studies—are highly interrelated, and the structure of the program must reflect those interrelationships (see Figure 4-1). Predictions cannot be performed without initializing observations; long-term observations cannot be justified without the predictions; models cannot be improved without parameterizations derived from process studies; the planning of process studies depends on the knowledge gained from empirical studies; and so forth.

In the interests of the strength of the program as a whole, no part of GOALS can be carried out at the expense of any other part. Conversely, all elements must be adequately funded and organized if major progress toward the program's objectives is to be made. Finally, it is important that the elements interact strongly so that advances in one element are available to the others.

To foster cooperation among scientists with interests in similar phenomena or in phenomena in a particular geographical region and to strengthen the links among the four elements of GOALS, consortia or principal investigator groups should be established, as illustrated in Figure 4-2. Consortia become essential for considering disparate but interlinked processes and for gathering and analyzing the data that relate to the feedback between processes.

For example, one consortium might focus on the suite of phenomena associated with short-term climate variations in the vicinity

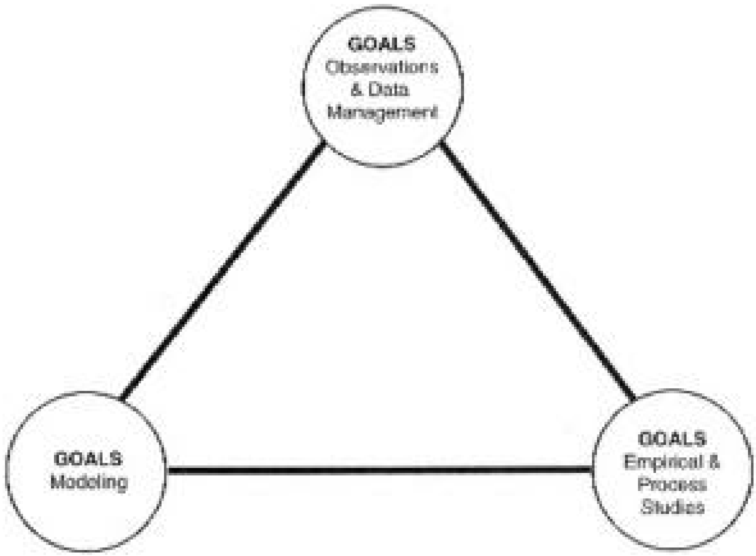

Figure 4-1 GOALS program architecture, showing the interrelated components of the program.

	Consortium #1	Consortium #2	P.I. #1	P.I. #2	P.I. #3
Empirical Studies	✓	✓	✓		✓
Process Studies	✓	✓			
Modeling	✓	✓		✓	
Observations		✓			

Figure 4-2 Illustration of the partitioning of GOALS research among the various program elements (rows) and the various consortia and principal investigators (columns). Examples of hypothetical consortium themes are given in the text.

of Australasia, the Indian Ocean, and the extreme western Pacific. A focus of the consortium might be the organization of a series of coordinated studies of relationships between the monsoon heat sources and the underlying SST gradients, flow through the straits separating the two oceans and its effect on the reflection of waves at the western boundary, the role of boundary currents in the western Pacific in the heat balance, and so on. Particular aspects of the transient variability in this region might be emphasized, such as 40-to-60-day waves, or cold surges, or the tendency for phase locking between ENSO and the annual cycle, which gives rise to enhanced quasi-biennial variability.

Another consortium possibly might focus on the suite of problems associated with atmosphere–ocean interaction on the cold side of the tropics (that is, the Atlantic and the eastern Pacific). The continental heat sources over northern South America and Africa do move, with considerable consequences for human populations. The cold-hemisphere oceans have a disproportionate influence on the variability of the large-scale zonal SST gradients. Substantial dividends could be gained from making the SST forecast correctly for this region. Phenomena of interest might encompass boundary-layer processes in the equatorial-cold-tongue/ITCZ complexes, stratiform cloud decks, and the American monsoon.

Still another possible consortium theme might be the local oceanic heat balances in contrasting regions of the tropical and extratropical oceans, with emphasis on understanding and modeling the SST variations.

Activities organized and coordinated by consortia may involve any combination of empirical studies, process studies, and model simulations. In some cases, long-term observations and/or field experiments might also be proposed. Regardless of the consortia organized, the GOALS program would reserve part of its resources to fund the efforts of individual principal investigators.

5

Data Management

The GOALS program would require a robust data management system. The data management plan would likely develop from current TOGA and post-TOGA data management plans. Being a broader study, however, GOALS would encompass new data sets from field experiments, specialized data sets, and data sets derived from new observational networks designed to complement existing global measurements. The amount of data used and produced by GOALS is expected to be significantly greater than that used and produced by TOGA. Moreover, unique requirements for GOALS would probably arise with the introduction of new operational observation platforms or techniques, portable self-describing data formats, novel data transmission technologies, and the development of technology such as larger mass storage systems. The benefits of cross-program science transfer and the likelihood of tight budgets in the future make paramount the need to share resources with other programs. Using facilities and expertise that are already developed and proven ensures both economy of effort and continuity. Also, the transition from a research to an operational mode that is proposed for GOALS has impacts on the budget process, funding sources, and data management responsibilities.

PRINCIPLES AND OBJECTIVES

Data management requirements should be driven by the science and operational requirements for data streams for both near-real-time and retrospective use. Data streams and data sets would be variable, with the type and format of the data differing, depending on their origin (such as new and existing observing systems, field research programs, and experimental programs). Attention to data quality and continuity would be imperative.

During the 15-year time frame of the program, hundreds of gigabytes of data would be collected and analyzed—and then used well beyond the lifetime of the program. (Data sets from the GARP Atlantic Tropical Experiment, for example, are still being used many years after the termination of the experiment.) Clearly, it would be essential that data sets and data streams from GOALS be safely archived and remain easily accessible to the research community.

As the number of users of data sets evolved—including modeling and satellite data sets, and in situ measurements such as those from TOGA-COARE and the Global Climate Observing System—the GOALS data management system would need to be able to handle new data streams. A data management plan to accommodate near-term efforts and to provide a framework for long-term goals would then be required. This would be particularly important with the emergence of the synergy between GOALS and other international programs that address global dynamics (for example, GEWEX, GCOS, GOOS, ACCP, WOCE, JGOFS).

The following list of principles and objectives should guide the development of a detailed GOALS data management plan:

1. Data are distributed as soon as possible, and there is full and open exchange of data and derived products.
2. Reanalysis is an integral part of the program; this necessitates assessable retention of observations in original form.
3. Sufficient metadata (quality control flags, instrument history, processing attributes, and so on), are provided so that researchers can evaluate the usefulness of the data.
4. An ongoing, collaborative effort is maintained between data managers and researchers to assess standards for the production of data sets.
5. Some data and data display tools are available on-line and in near real-time.
6. Backup data sets are archived to accommodate any change in parameters or algorithms that would affect derived quantities.
7. Other data management activities, such as the EOS Data and Information System (EOSDIS) are monitored and evaluated for their relevance and applicability to GOALS.

8. Real-time and delayed-mode four-dimensional data-assimilation systems provide fields to complement observations.
9. There is a distributed data archive and access system involving the full range of regional, national, and world data centers.
10. An on-line service is created with high-level project information (for example, the progress of an experiment, program information, availability of data), perhaps similar to other information systems currently in use, such as those for WOCE, TOGA-COARE, and Storm-scale Operational and Research Meteorology (STORM).

DATA CENTERS

Considerable infrastructure already exists to process, archive, and distribute Level I (radiance and similar unprocessed measurements), Level II (geophysical quantities), and Level III (assimilated or blended analyses) data sets. However, that infrastructure must be maintained and, in many instances, expanded. Similar to TOGA's data centers, existing institutions would be relied upon to a large extent to manage specialized data streams and data sets. Examples already exist in the TOGA program, where existing institutions have taken on the task of quality control and general support, such as:

- The Tropical Sea Level Data Center (Hawaii) produces Level II-B sea level data,
- The Tropical Ocean Subsurface Data Center (IFREMER, Brest, France) generates Level II-B subsurface temperature and salinity data,
- The European Centre for Medium-Range Weather Forecasts (ECMWF) processes atmospheric Level III-A global meteorological fields,
- The TOGA Marine Climatology Data Center (U.K. Meteorological Office) produces Level II-B marine surface meteorological data,
- The Global Sea-Surface Temperature Data Center (NMC) performs Level II-A, III-A, and III-B processing of SST observations, and
- The TOGA Upper-Air Data Center (New Delhi) has responsibility for upper-air observations.

Complementing these data centers are several TOGA-related institutes, universities, and national services that hold or produce data sets of interest to TOGA researchers. Examples are NOAA's Atlantic Oceanographic and Meteorology Laboratory (AOML) for surface current drifter data; NOAA's Pacific Marine Environmental Laboratory (PMEL) for near-real-time data from the TOGA-TAO array; Florida State University for pseudo-wind stress fields; and WOCE Data Assembly Centers for various types of mooring, float, and drifter data, and sea-level and upper-ocean thermal data. In most cases, World Data Centers A and B for meteorology and oceanography are the final (delayed-mode) repository for all TOGA data sets.

To investigate the feasibility of predicting short-term climate variations, quality-controlled meteorological and oceanographic data from established data centers would be required to initialize forecast models. This would include the analysis of multivariate fields and considerable data processing and production activities, that is, data assimilation and modeling. Model initialization would require the merging and gridding of various fields through multivariate optimal interpolation or other techniques. This operation would entail an evolving set of quality-control procedures. Model runs would create large quantities of output that would have to be documented, archived, and distributed on various media. To achieve these goals, advanced data archiving, retrieval, and visualization capabilities would be required for both assimilation and forecast products. The dissemination of these data and information throughout the research community, and to other pertinent interests, would be of paramount importance to the program. This dissemination capability would require investments for leveraging existing and planned interoperable data systems that could provide GOALS scientists with access to data sets via common interfaces. The communication backbone for such a system must be capable of transmitting millions of bits per second.

To achieve its objectives, GOALS is very dependent on ongoing efforts within NASA, NOAA, National Science Foundation, U.S. Department of Defense, and U.S. Department of Energy data centers for the necessary infrastructure to support such a data management system. It is hoped that this in place network of data processing centers and data repositories would be able to provide expeditiously the GOALS program with some important state-of-the-art data management capabilities.

A major commitment of the GOALS program would be the assembly and analysis of a 30-year (1971-2000) climatic data set to examine seasonal-to-interannual variability. This effort would involve developing ways to incorporate remotely sensed data, as well as multivariate, relatively and absolutely inhomogeneous, and sparse data into coupled ocean–atmosphere–land models. The resulting data sets would also facilitate empirical studies of the predictability of the coupled system. Strong communication links and interoperability between major data centers and data-distribution centers could be required.

6

Relationship of GOALS to Other Programs

There are strong scientific linkages among research problems on time scales both shorter and longer than those to be considered by GOALS. These scientific linkages inevitably lead to programmatic linkages; both the scientific and programmatic linkages are described in this chapter.

Ongoing efforts in dynamic extended range forecasting (DERF), which nominally covers 7-14 days in advance, would complement the modeling component of GOALS extremely well. This is especially the case for the dynamical prediction of seasonal averages using uncoupled and coupled ocean–land–atmosphere models. Although the role of the ocean in DERF is minimal, modeling and prediction of seasonal-to-interannual variations involving SST changes on these time scales would help to define more precisely the ranges at which SST changes begin to exert an influence on DERF. The GOALS prediction research strategy should include the predicting of SST and DERF to see if more detailed seasonal predictions can be made. Because the overlap between DERF and GOALS predictions is centered on predictions one season in advance, the seasonal prediction is expected to produce fruitful interactions between members of the DERF and GOALS research communities.

Observations and predictive capabilities for seasonal-to-interannual time scales will aid in understanding and predicting decadal variations, as well as the effects of radiatively active (greenhouse) gases on time scales of 100 years or more. The tools of prediction on decadal and longer time scales are similar to those used for prediction on time scales of interest to the GOALS program. A major difference is that GOALS can confine its interest to the upper ocean and to the atmosphere's current composition of gases and aerosols, whereas deeper parts of the ocean and changing chemical composition of the atmosphere must be considered as the time scale of interest increases.

Simulating an accurate climatological mean state is a crucial part of longer-term climate modeling. Interannual variability is an important part of that climatological mean state. In particular, a world without interannual variability would have a different mean surface temperature from that of the actual world. Figure 6-1, a product of the Zebiak-Cane model, shows the long-term average of SST-anomaly fields from ENSO. Clearly, the ENSO itself warms the eastern Pacific by about 1K relative to the western Pacific and it warms the tropical Pacific as a whole relative to climatology. It is therefore clear that a climate model that did not simulate ENSO correctly, including its mean intensity and frequency distribution, would not be able to simulate the global surface temperature correctly.

Climate models must get seasonal-to-interannual variability correct to model the current climate correctly. They must also model changes in interannual variability correctly to model climate change correctly. It has often been pointed out that a change in the intensity and regularity of ENSO would have an effect on the mean climate and that greenhouse warming may express itself partially through such changes (Zebiak and Cane, 1991; Meehl et al., 1993; Trenberth and Hurrell, 1994). Since the coupled ocean–atmosphere—land models developed for prediction of seasonal-to-interannual variations in climate bear a close relationship to the models used for prediction of decadal and longer climate variations, it is clear that advances in modeling short-term climate variability will assist in modeling longer-term climate variability.

Finally, it is important to note that the World Weather Watch is a measurement system designed for weather prediction but, when extended over long periods of time, it is also useful for climate measurements. So too, an upper-ocean measurement system for climate prediction of seasonal-to-interannual time scales, if extended over long periods of time, will be useful for climate assessment and prediction for much longer time scales.

ENSO is known to affect the carbon dioxide (CO_2) content of the atmosphere. When an El Niño event occurs, atmospheric CO_2 usually increases above its usual level. This has been attributed to reduced uptake of CO_2 by terrestrial vegetation suffering from the decreased rainfall in Southeast Asia. In the equatorial Pacific, however,

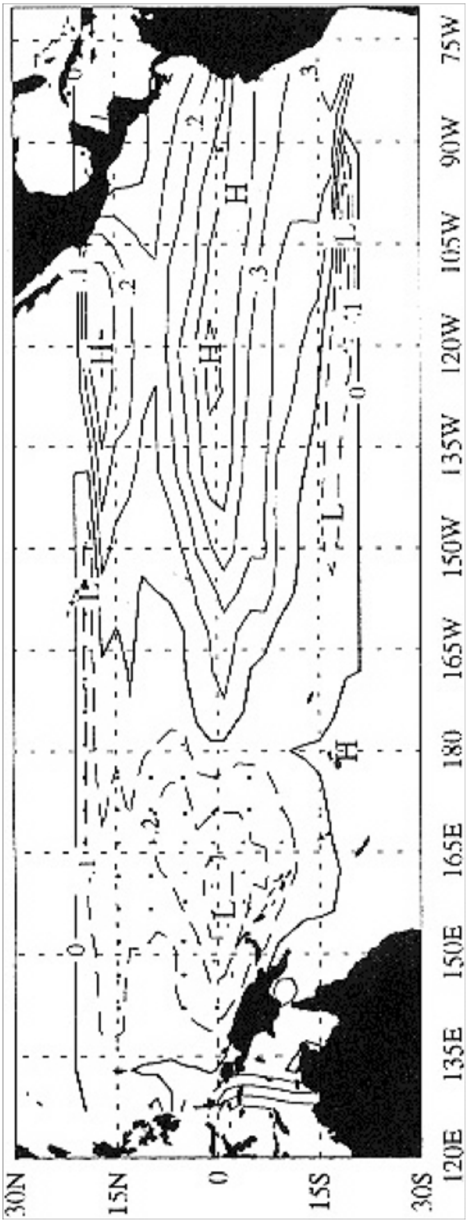

Figure 6-1 1000-year mean SST-anomaly fields (K) for ENSO conditions from the Zebiak-Cane coupled model.

the upwelling of carbon-rich waters during ENSO acts to reduce atmospheric CO_2 from its usual level (see, for example, Feely et al., 1987). The terrestrial effect is larger than the ocean effect, resulting in a small net increase of atmospheric CO_2. However, long-term changes in the intensity and regularity of ENSO due to greenhouse warming could alter the rates of these feedback processes and thus alter the greenhouse warming.

COLLABORATIVE EFFORTS

Regular and systematic forecasting by coupled numerical models has begun at a number of institutions and is being proposed for the IRICP. It is expected that the GOALS research community would collaborate with systematic forecasting activities so that the problems uncovered in forecasting could become active research areas for GOALS. It is expected that those organizations engaged in systematic forecasting would be cognizant of GOALS research so that advances and improvements made in understanding basic physical processes could be incorporated into forecasting models and procedures.

GOALS would organize research in support of international prediction activities as a major contribution to CLIVAR. Within the United States, research organized by GOALS would form one leg of the research-observations-predictions tripod illustrated in Figure 6-2. Note that the relationships between programs implied by Figure 6-2 mirror the structure of the GOALS Program itself, as summarized schematically in Figure 4-1. These three legs must interact with each other strongly and bear equal weight in the prediction enterprise: the entire structure would fall if one leg became out of balance with the others. This relationship has precedent in weather prediction programs and was incipient for TOGA. However, organization for GOALS is complicated by the necessary inclusion of both the oceanographic and land aspects of climate predictions.

The collaborative programs that are described briefly below deserve specific mention due to their close scientific linkages to GOALS and their potentially strong contributions to the program.

Global Climate Observing System (GCOS) and Global Ocean Observing System (GOOS)

GOALS would capitalize on the global observations and data management systems for climate (GCOS, the Global Climate Observing System). It will also foster the development and implementation of new observing technologies that will ultimately become part of both

GCOS and GOOS (Global Ocean Observing System). Similarly, GOALS investigators would utilize gridded ocean data sets created as input for numerical prediction models of the coupled atmosphere—ocean system as part of the IRICP. Their research would contribute to improvements in these models.

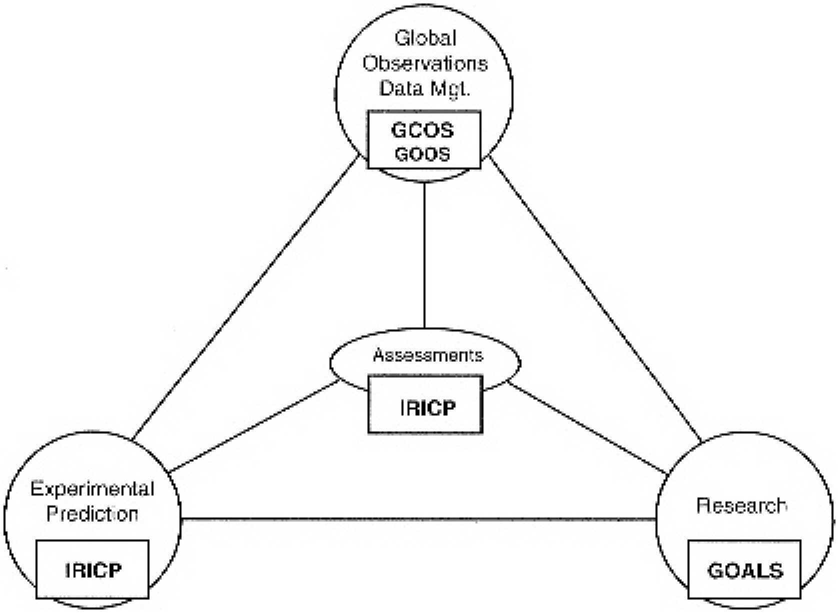

Figure 6-2 Functional relationship between GOALS and the other interannual research components of the U.S. Global Change Research Program. The GOALS program will serve as the principal focus for basic research on seasonal-to-interannual time scales. The proposed Global Climate Observing System (GCOS) and the proposed Global Ocean Observing System (GOOS) would provide observations worldwide, and the proposed International Research Institute for Climate Prediction (IRICP) would provide experimental prediction and assessments of seasonal-to-interannual climate variations.

Global Energy and Water Cycle Experiment (GEWEX)

The primary objective of GEWEX is to understand, model, and predict the characteristics of the global hydrologic cycle and the related energy fluxes. Currently GEWEX is strongly focused on land—atmosphere processes and analysis of global atmospheric water vapor. The GEWEX process studies in the Mississippi Basin (GEWEX-Continen tal-scale International Project [GCIP]) will quantify the temporal variability of the water and energy cycle, test and improve land-surface parameterizations, and improve macroscale water-budget models for grid-scale and subgrid-scale GCM applications.

By contrast, GOALS seeks to understand, model, and predict climate variability on seasonal-to-interannual time scales. As a natural outgrowth of TOGA, GOALS would initially emphasize ocean—atmosphere interactions. Although there are no plans for GOALS to organize land-process studies, GOALS must include considerations of the land surface (soil moisture, snow cover, and so forth) to understand climate variability.

GEWEX focuses on a major element of the climate system, whereas GOALS would consider the variability of the climate system itself. Clearly, GOALS and GEWEX can undertake complementary activities, with little redundancy; GEWEX could gain substantially from the GOALS research on climate system predictability, modeling, and prediction. GOALS would need to benefit from the GEWEX research on the global hydrologic cycle and major regional hydrological processes, as well as exploit GCIP products and parameterizations. The GEWEX Asian Monsoon Experiment (GAME), related to TRMM, would also provide observations and understanding of significance to GOALS. GEWEX may well benefit from the GOALS estimates, in space and time, of the atmospheric water vapor moving over the continents and its variability.

GOALS is proposed as a phased project, starting from the global tropics, then considering the influence of the tropics on higher latitudes, and finally incorporating higher-latitude regions in the examination of climate variability. This phased structure maximizes the opportunity to develop collaboration between GOALS and GEWEX, and to gain optimum benefit from the successes of the two programs.

World Ocean Circulation Experiment (WOCE)

The World Ocean Circulation Experiment (WOCE) was established by the WCRP to address the questions of ocean heat transport and the role of the ocean in climate change on decades-to-centuries time scales. WOCE emphasizes study of the transfer of heat, momentum, and greenhouse gases between the atmosphere and the ocean. The primary goal of WOCE is to model the ocean's present state, to predict its future state, and to predict feedbacks between climate change and the ocean circulation. WOCE includes plans to study the surface and subsurface circulation of the global ocean, with an 8-year field program that ends in 1997. Synthesis and modeling efforts will con tinue well into the next century. As was noted with respect to GEWEX and GOALS, the WOCE and GOALS objectives are complementary, with little redundancy. Of direct relevance to GOALS are the description of the ocean's present circulation and its variability, air-sea boundary-layer processes, the role of exchange among different ocean basins, and the effect of the oceanic heat storage and transport on the global heat balance. WOCE's monitoring of the upper ocean would certainly contribute to GOALS and, in turn, GOALS would eventually support and augment WOCE upper-ocean observations through the extension in time and space of the TOGA TAO array.

Atmospheric Radiation Measurement (ARM)

The goal of the U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) program is to improve the treatment of cloud-radiative forcing and feedbacks in GCMs. The ARM program is providing an experimental testbed for the study of important atmospheric processes, particularly cloud-radiative forcing and feedback. There is a particular emphasis on testing parameterizations for use in atmospheric models.

Five primary Cloud and Radiation Testbed (CART) sites[1] will be established during the next 5 to 10 years and will be operated for at least 10 years. Their five primary locales, in the proposed order of implementation are the:

1. Southern Great Plains, United States (now operational);
2. Tropical Western Pacific;
3. North Slope of Alaska;
4. Eastern Ocean Margins; and
5. Gulf Stream, off the U.S. east coast.

The first stage of the project at the Tropical Western Pacific site, will be the phased deployment of three to five Atmospheric Radiation and Cloud Stations (ARCS) in the region beginning in 1994. An ARCS will measure solar and terrestrial radiation components, cloud properties, and meteorological variables. The data will be transmitted back to a data center in the United States and will be available to any interested party. The Tropical Western Pacific site will be of particular interest for ENSO studies and improved parameterizations

[1] This number may be reduced due to budget constraints.

of radiative forcing from the ARM program will be of great value in modeling seasonal-to-interannual variations.

Atlantic Climate Change Program (ACCP)

The Atlantic Climate Change Program (ACCP) has focused primarily on decadal time scales of climate variability. However, program objectives also explicitly include study of the variability that is associated with interannual and seasonal time scales. Therefore, there is a direct intersection of program objectives with those of GOALS. The goals of the ACCP and GOALS are clearly complementary, with the Atlantic Ocean forming a common geographic focus.

The ACCP and GOALS should have common observational components. These observational studies would be designed to examine specific processes that are thought important in the exchange of energy and mass between the atmosphere and ocean, and between the atmosphere and land. They would support evaluation of subgrid-scale parameterizations in the numerical climate models to be used in both programs.

Other Programs

The potential interaction of GOALS with national and international programs is not limited to the major programs described above. The Surface Heat and Energy Budget of the Arctic (SHEBA) program, which will provide critical observations at high latitudes, would be of value to GOALS in meeting its long-term objectives. Atmospheric chemistry programs are expected to be the source of information on chemistry and radiation data and models, as well as information on the role of volcanic aerosols. GOALS program management and science teams would also examine possible interactions with the Joint Global Ocean Flux Study (JGOFS), the primary focus of which is understanding the carbon cycle, but which may develop data sets complementary to GOALS activities.

7

GOALS Program Management

The GOALS program is conceived as a complex scientific endeavor that would require long-term commitments and, as with the TOGA program, multiagency support. It would contribute to a larger international program, the World Climate Research Program's CLIVAR initiative, with the duration of the two programs—from 1995 to 2010—coinciding. Program management for GOALS would be modeled on the structure so successfully employed in the TOGA program, a prototype for programs designed to address complex issues of global climate change.

Figure 7-1 depicts the proposed organizational structure for GOALS and its relationship to CLIVAR. The GOALS program would be managed in a tripartite fashion, with a project office (GOALS Project Office), a scientific oversight body (NRC, with its Climate Research Committee and GOALS Panel), and a group of participating federal agencies.

The federal agencies would be responsible for implementing GOALS through coordinated funding of research grants. An interagency GOALS Project Office would serve as a focal point for the implementation of the national research effort. The responsibilities of the GOALS Project Office would include:

- Organization of U.S. participation in the international CLIVAR program in relation to (1) components of the observing system, (2) data management, (3) basic and applied research, and (4) modeling and prediction;

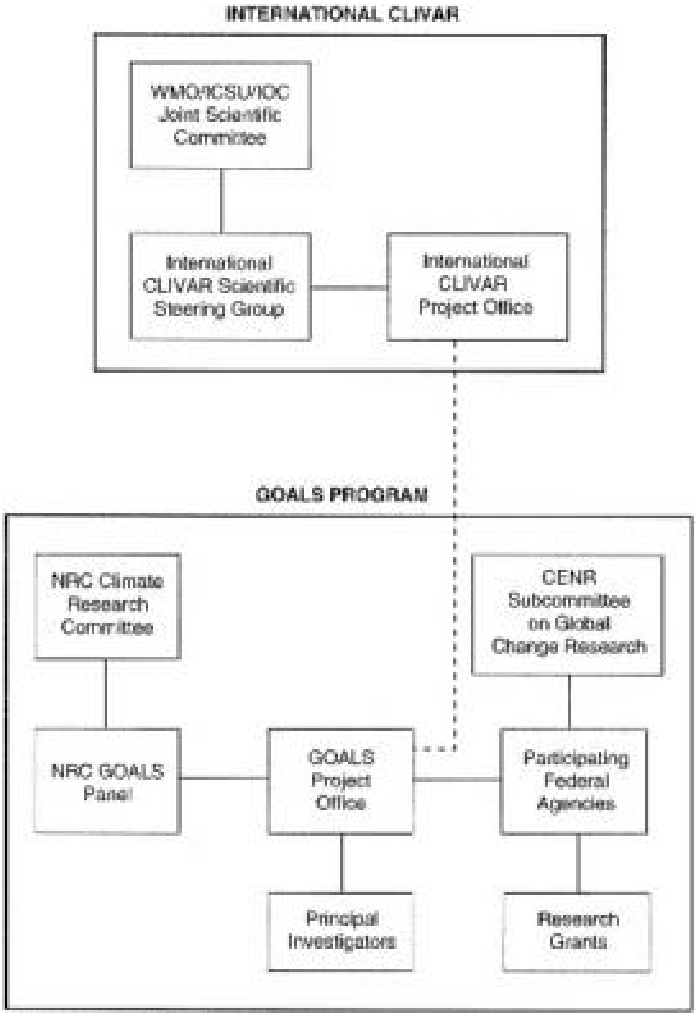

Figure 7-1 GOALS program management structure and its relationship to the international CLIVAR program. Shown are relationships among oversight committees, science panels, project offices, federal agencies, and groups participating in the GOALS program. Also depicted are relevant components of the CLIVAR management structure and its principal communication link to the GOALS program through the project offices (dashed line).

- Preparation of a multiagency plan to address the implementation of GOALS;
- Coordination of multiagency long-range budget estimates and preparation of annual budgets for GOALS research; and
- Regular reporting to the NRC GOALS Panel on the status of the program and providing for communication with other U.S. programs (for example, Atlantic Climate Change Program) and international programs (such as the Global Energy and Water Cycle Experiment) as needed.

With oversight of the Board on Atmospheric Sciences and Climate through its Climate Research Committee (CRC), the GOALS Panel would provide scientific guidance for the program. The responsibilities of the GOALS Panel would include:

- Providing overall scientific leadership—with regular review and guidance on long-range scientific policy, planning, progress, and priorities—to the GOALS Project Office and involved agencies;
- Regularly reporting to the CRC on the panel's involvement in GOALS plans and activities, and receiving guidance from the CRC on GOALS matters in the context of the overall U.S. climate research program; and
- Reviewing plans, making recommendations on priorities, and otherwise providing inputs to the international CLIVAR program.

Principal investigators and consortia would carry out much of the actual implementation of the GOALS scientific plans. As the needs of the program dictate, the GOALS Project Office would invite groups to prepare coordinated sets of research proposals designed to address specific objectives of GOALS.

Close coordination between GOALS and international CLIVAR would be maintained through a formal link between the project offices for the two programs and an informal liaison between the GOALS Panel and the International CLIVAR Scientific Steering Group.

Appendices

A

Present Status of Short-Term Climate Prediction

The 10-year (1985–1994) TOGA program was launched to study the predictable cycle of ENSO events in the tropics and their correlation with quasi-stationary features of atmospheric circulation at higher latitudes. One remarkable success of TOGA has been the rapid development of a theoretical understanding of ENSO as a dynamical phenomenon of the coupled ocean–atmosphere system. The TOGA research community now understands several basic mechanisms of ocean–atmosphere interactions that contribute to interannual variabilities; some insight into the interplay between these mechanisms has been developed. A hierarchy of coupled models (simple, intermediate, hybrid, and full GCMs) has simulated many aspects of tropical interannual climate variations. In addition, predictions are being made of the future evolution of aspects of ENSO using coupled models along with the wind and thermal data collected by the TOGA observing system.

The basic concept exploited in ENSO prediction is that ocean–atmosphere instabilities occur in the tropics at large spatial scales and low temporal frequencies. As first shown by Philander et al. (1984) in a model consisting of a simplified "shallow-water" atmosphere coupled to a simplified shallow-water ocean, unstable modes could arise as a result of the coupling of otherwise stable systems. In much the same way that ordinary weather disturbances go through a characteristic cycle of rapid growth and decay, ENSO disturbances have a life cycle with some repeating characteristics. Although the cycle is often irregular, many of ENSO's slowly evolving features can be simulated and predicted by models that include only the tropical Pacific Ocean and the atmosphere above it. Some of the predictability comes from the fact that low-frequency atmosphere—ocean coupling is governed by physical laws that cause certain parts of the ENSO cycle to follow slowly and inevitably after others.

Predictability is a property of a dynamical system, whether natural, mathematical, or mechanical. It can be estimated from a single or multivariate time series produced by the system in question. Ideally, we would like predictability estimates of the coupled ocean–atmosphere–land system on seasonal-to-interannual time scales from direct measurements, but observed time series are much too short for making such estimates reliably. Therefore, direct estimates from oceanic, atmospheric, and land data have to be supplemented by predictability estimates from model systems. The accuracy of these estimates increases with the length of record available. The best predictability estimates can be obtained for the simplest systems. However, the reliability of model estimates as approximations of the coupled climate system's real predictability increases with the number of other features of the real system that are accurately simulated by the model in question. Thus, predictability estimates should be pursued by observational studies across a complete hierarchy of models, from the simplest mechanistic ones to the most highly resolved GCMs. One way of estimating predictability is by making ensembles of predictions.

It is now well understood that the ENSO phenomenon is a coupled phenomenon arising from the interaction of the atmosphere with the ocean, so that dynamical simulation and prediction must be based on coupled atmosphere—ocean models. While simple analog models of coupled atmosphere–ocean interactions (Battisti and Hirst, 1988; Schopf and Suarez, 1989; Cane et al., 1990; Neelin, 1991; Wakata and Sarachik, 1992; Jin and Neelin, 1993) have proven illuminating in interpreting and explaining the grosser aspects of ENSO, more complex coupled dynamical models are needed for more detailed and accurate simulations and predictions.

At present, there are five documented and ongoing routine prediction systems for ENSO, each of which demonstrated skill at least a season in advance. Two of the systems are statistical: one by Barnett and collaborators (Graham et al., 1987a,b), the other by investigators at the Max Planck Institute for Meteorology (Xu and von Storch, 1990). A third method developed at Florida State University (FSU) is a statistical-dynamical technique using only an ocean model (Inoue and O'Brien, 1984, 1986). The fourth method is based on a dynamical coupled ocean–atmosphere model developed at Lamont-Doherty Earth

Observatory by Zebiak and Cane that prescribes the mean climatology and predicts the anomalies (Cane et al., 1986; Zebiak and Cane, 1987). The fifth method is based on coupling complex models of the atmosphere and ocean (Latif et al., 1992; Ji et al., 1994). There are additional statistical climate forecasting schemes currently being developed based on neural nets and singular spectrum analysis (Keppenne and Ghil, 1992). Other dynamical forecasting schemes are being developed with coupled GCMs using data ingestion and assimilation methods. These and other forecasts are reported monthly by the NMC in the "Forecast Forum" section of the *Climate Diagnostics Bulletin* and in the *Experimental Long-Lead Forecast Bulletin*.

The coupled ocean-atmosphere model of Zebiak and Cane (1987) (hereafter referred to as the ZC model) has produced what are considered to be the longest-range successful numerical forecasts of ENSO events yet produced. The warm phases of the 1986–1987 and 1991–1992 events were predicted more than one year in advance, and skillful hindcasts of previous events support the validity of the approach. The ZC model is an anomaly model in which the annual climatology is specified and the interannual variability is calculated. Zebiak and Cane showed that coupling a diagnostic atmosphere to a shallow-water ocean (with the annual cycle of the coupled system specified) leads to anomalies that resemble ENSO closely, both spatially and temporally. The model has been investigated and analyzed extensively, and the mechanisms for the model ENSO (the "delayed oscillator mechanism") has been described in detail (Battisti, 1988; Battisti and Hirst, 1988; Battisti, et al., 1989). This same model was used to predict the onset of the 1986–1987 warm phase of ENSO a year in advance (Cane et al., 1986). That the ZC model is intrinsically predictable was demonstrated by Goswami and Shukla (1991), who showed that errors in initial conditions grow rather slowly (initial doubling times on the order of 6 months), so that knowledge of the initial state of the coupled system seems to contain foreknowledge of the state of the system up to a year or so in the future. This slow error-growth rate is a direct consequence of the inertia of the ocean in the ENSO cycle. The predictability of the future evolution of the coupled atmosphere–ocean system is embedded in the initial state of the ocean and is realized in the slow evolution of the ENSO cycle.

To initialize the ZC model, the observed monthly FSU-analyzed ship wind field for the Pacific is converted to surface stress specified over the model Pacific. Then, the atmosphere is coupled to the ocean, the system generates its own surface wind and SST fields, and the coupled model is subsequently allowed to run freely. There is an initial error in that the model-generated winds disagree with the im posed FSU winds at the initial time. Predictions of area-averaged SSTs in the Pacific Ocean are then made for up to 18 months in advance. Predictive skill is highly dependent on the time of year from which the prediction is made, with predictions from the northern spring having the lowest skill (Cane and Zebiak, 1987; Cane, 1991).

The work by Latif and collaborators (1993a) and by Leetmaa and Collaborators (Ji et al., 1994) are the only published examples to date of predictions made by fully-coupled ocean and atmosphere GCMs. Although the mean climate of the coupled model differs considerably from the observed climate, the skill of predicting interannual variations is comparable to that of other models.

It is known that the skill for predicting the phases of ENSO is seasonally varying. The Southern Oscillation is weakly phase-locked with the annual cycle (Rasmusson and Carpenter, 1982; Trenberth and Shea, 1987), with extreme values occurring preferentially at certain times of the year. Transitions between Southern Oscillation Index (SOI) values from one sign to the other occur most often in the April–June period. The structure of the lagged autocorrelation of the SOI shows relatively small persistence until April–May, when it increases substantially with significant values out to about 8 months. The immediate conclusion is that something often occurs in the late northern spring that is independent of ENSO but that can influence its development. Interestingly, Barnett (1983; 1984a,b) showed a strong relationship between the interannual fluctuations of the Indian Ocean monsoon and the Walker circulation, with the coupling of the monsoon and the Pacific trade winds depending on the phase of the annual cycle.

A marked seasonal reduction in skill in predicting SST anomalies in the eastern equatorial Pacific (Cane et al., 1986; Barnett et al., 1988; Latif and Graham, 1992) is almost certainly related to this seasonal structure of the Southern Oscillation, which has been attributed to the somewhat variable and rather rapid onset of the Asian summer monsoon by Webster (1987) and Webster and Yang (1991). If the intensity of the monsoon is predictable (for example, Shukla, 1987) and the influences of the Asian monsoon on the Pacific Ocean and the overlying atmosphere are included in our prediction models, would we see a significant increase in prediction skill for ENSO onset?[1]

[1] Most ENSO models presently do a poor job of simulating the termination of warm events. Observations show that the termination process begins with a reversal of westerly winds to easterly winds in the far western Pacific, a reversal not included in the Pacific-only models of ENSO. This reversal may be associated with the monsoons.

The answer depends on the degree to which air–sea interactions in the maritime continent and western Pacific are well-simulated by the prediction model. Relatively small changes in the way that atmosphere–ocean coupling is parameterized can result in what may be called the SST instability mode (see, for example, Barnett et al., 1991; Latif et al., 1991; Neelin, 1991). This eastward propagating mode has been seen previously in observations (Gill and Rasmusson, 1983) and in some intermediate models (Anderson and McCreary, 1985a,b; Yamagata and Masumoto, 1989). Although relatively slow ocean dynamics dominates, as in the "delayed oscillator" mechanism, this mode appears to be more sensitive to local atmospheric forcing in the western Pacific, where SST is high and coupling is strongest. The relative forcing of these two modes of interannual variation may account for some of the differences between ENSO events and may be important in predicting the strength of the Asian monsoon.

Additional skill in ENSO prediction could arise from the recently made distinction between two modes of variability of the tropical ocean–atmosphere system, quasi-biennial (Trenberth, 1975, 1980; Trenberth and Shin, 1984) and lower-frequency (Rasmusson et al., 1990). The separation of the broad 42-month peak identified by Rasmusson and Carpenter (1982) into these two sharper peaks holds promise for the better physical understanding of possible distinct oscillation mechanisms, as well as for ENSO prediction beyond a year. Barnett et al. (1991) suggested nonlinear interactions between these two modes, Jiang et al. (1992) described the standing and traveling patterns of SST and surface zonal wind associated with them, and Keppenne and Ghil (1992) exploited the greater regularity of the two separate modes to demonstrate very high hindcast skill of the SOI for up to 30 months. Both diagnostic evidence and hindcasting exercises show that large warm or cold events seem to be associated with the two separate oscillations being in phase.

On the basis of the skill and predictability demonstrated by various models, the TOGA Program on Prediction (T-POP) was formed to institute a routine interannual prediction effort. This effort uses the best available model and data assimilation procedure to extend the skill and spatial and temporal range of the predictions, and to do the research and development necessary to accomplish these objectives (see Cane and Sarachik, 1991). T-POP was also formed to take advantage of the skill already indicated by statistical models and by the ZC model (see Barnett et al., 1988), and to exploit to the extent possible the skill inherent in interannual predictions. It was recognized that the ENSO signal offers the best initial hope for predictions, since the existence of a nearly periodic cycle in the tropical

Pacific implies a certain predictability once the cycle is ongoing (Sarachik, 1990). In particular, the great potential of subsurface data for the tropical Pacific provided by the TOGA observing system needs to be exploited.

ENSO is not the only important source of seasonal-to-interannual variations. The annual cycle and some important interannual variations of climate are due to processes and phenomena other than those associated with ENSO. For example, variations of rainfall in Brazil and the Sahel are subject to interannual fluctuations that are linked to Atlantic SST variations (Hastenrath, 1990). To achieve the objective of predicting non-ENSO signals in climate, other major climate signals must be identified and understood. The continuum, or background spectrum, of natural climate variability must also be recognized and it must be determined whether these fluctuations are predictable, especially if they influence ENSO predictability.

Much remains to be done to assess the potential for predicting tropical disturbances and their influence on the extratropical circulation. The skill of ENSO forecasts varies markedly with season. The relationship of ENSO to monsoon rainfall over the tropical and subtropical land masses is not well established. Furthermore, the understanding and successful simulation of the extratropical response to the tropical sea-surface anomalies is proving to be a more difficult problem than anticipated at the outset of TOGA. Coupled ocean–atmosphere–land models are proving to be unusually sensitive to errors in component systems, leading to problems in correctly simulating the climatology and the spectrum of variations. In the tropical Pacific, it appears as if the annual cycle is harder to simulate than interannual variations without annual forcing. The annual cycle of SST in the eastern Pacific, for example, seems to be in phase with the heat flux into the ocean, rather than out of phase as in ENSO variations. These heat fluxes also seem to be sensitive to stratus clouds, which induce a positive feedback to SST at low temperatures but a negative feedback at high temperatures. It is becoming even more clear that a complex mix of processes is at work in the annual cycle.

As the complexities of fully coupled GCMs are being explored, considerable effort is being devoted to the problem of data assimilation and initialization. Both atmospheric and upper-ocean data need to be inserted, in a dynamically consistent manner, into a coupled model to gain the best possible estimate of the initial state from which predictions are made. Such a scheme should be multivariate—able to handle data of a variety of types, such as velocity, temperature, and pressure. It should produce estimates of the full three-dimensional structure of the atmosphere and ocean temperature and

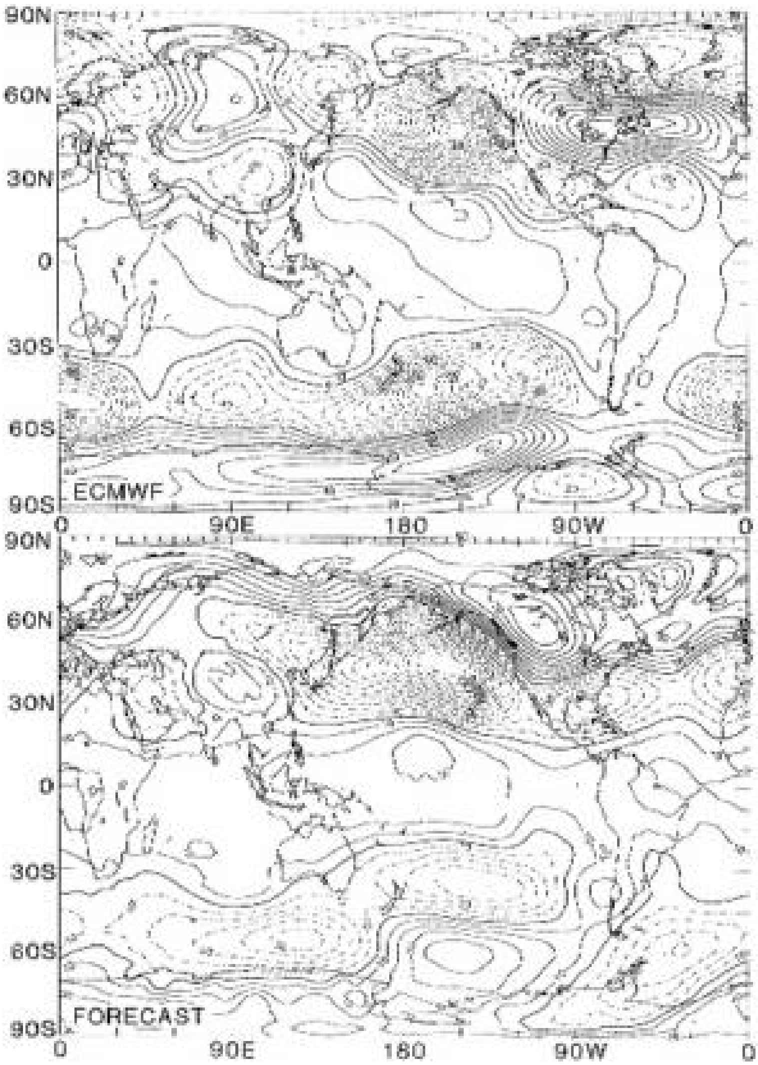

Figure A-1 Observed (upper) and predicted (lower) 500-mb height-anomaly fields for the warm ENSO event of the northern winter of 1982–1983. The observations are from analysis by the ECMWF; the prediction is an average of three forecasts, made at a lead time of 6 to 8 months, by Bengtsson et al. (1993). Solid contours are associated with positive height anomalies and dashed lines show negative height anomalies.

velocity fields. Finally, it should provide some indication of the accuracy of the estimate of that state.

No complete prediction system using coupled GCMs and a fully coupled data ingestion and assimilation procedure is yet in regular operation, although major pieces of such an operational system have been developed at the National Meteorological Center (Ji et al., 1994). Considerable progress is being made in constructing and evaluating such systems. While this process continues, various hybrid-prediction schemes are showing considerable promise.

A recently developed scheme by Bengtsson et al. (1993) uses a hybrid coupled model (a statistical atmosphere coupled to an ocean GCM) to predict SST in the tropical Pacific 6 to 8 months in advance of the winter season. The SST is then used as a lower boundary condition for a relatively high-resolution atmospheric GCM. Good predictions of the 500-mb height field over the northern Pacific and west coast of the United States result, with potentially useful skill for predicting rainfall over the western part of the United States (see Figure A-1). A similar scheme is under development at the National Meteorological Center.

B

The 1993 GOALS Study Conference

The GOALS Study Conference was held in Hawaii on 1–3 March 1993, with about 110 participants. The conference was arranged to receive maximum inputs from the scientific community on the plans for observations, modeling, and research in the post-TOGA period. It was organized around a number of scientific questions, each of which was introduced by an invited speaker. Following the scientific presentations, the Study Conference broke into three working groups —modeling, observations, and empirical/process studies. This procedure gave all attendees an opportunity to provide input. The Study Conference agenda and list of participants follow.

Climate Research Committee
GOALS STUDY CONFERENCE
East-West Conference Center
1777 East West Road
University of Hawaii at Manoa, Honolulu, Hawaii
March 1–3, 1993
Final Agenda

Objective: To more fully define the science for GOALS and to prepare a final document reflecting the GOALS science objectives and research strategy.

MONDAY, MARCH 1, 1993

Keoni Auditorium

0900	Welcome and Opening Remarks	Barry Raleigh William Sprigg Jagadish Shukla
Morning Session Chair: Klaus Wyrtki		
0920	GOALS and Climate and Global Change in the United States	Otis Brown
0940	CLIVAR	Gordon McBean
1020	BREAK	
1040	TOGA	Mark Cane
1120	GOALS Overview	Ed Sarachik
1140	LUNCH	
Afternoon Session Chair: Tetsuzo Yasunari		
Science Questions:		
1300	1. What are the structure and dynamics of the seasonal cycle of the coupled ocean-atmosphere-land system and what are the reasons for its large spatial variability over the globe?	George Philander

1340	2. What is the nature of the global interannual climate variability and what is its relationship to the seasonal cycle? What processes give rise to such variability? Can our understanding of this variability be exploited for prediction?	Dennis Hartmann
1420	3. What is the role of the slowly varying global boundary conditions at the earth's surface (SST, sea ice, snow cover and land moisture) in determining the nature of the interannual variability of the global atmosphere?	Jagadish Shukla
1500	BREAK	
1520	4. What determines low-level convergence of moisture in the tropics over water, land, and land in the proximity to water? In other words, what determines the location of the thermal sources?	Edwin Schneider
1600	5. What is the nature of tropical-extratropical interactions? In particular, what is the role of tropical SST anomalies in perturbing the extratropical atmosphere, and in generating extratropical SST anomalies through the atmosphere? For what regions of the globe can accurate predictions of tropical SST anomalies be translated into skillful regional climate forecasts one or more seasons in advance?	Gabriel Lau
1640	RECESS	
1730 to 1930	RECEPTION at the East-West Center Lanai, hosted by JIMAR	

TUESDAY, MARCH 2, 1993

Keoni Auditorium

Morning Session Chair: Gordon McBean

0830	6. What improvements in coupled ocean-land-atmosphere models, convection, mixing and in particular the processes that determine the coupling of the atmosphere and ocean are needed for seasonal to interannual predictions?	Carlos Mechoso
0910	7. Are there interactions between interannual and interdecadal variability? If so, what is the nature of these interactions? Are there similar or different mechanisms at work on these two time scales?	Michael Ghil
0950	BREAK	
1010	8. What is the role of high frequency fluctuations in the tropics and mid-latitudes in seasonal to interannual climate variability and predictability?	Roger Lukas
1050	9. What measurements of the global upper ocean and land surface are required to initialize the coupled models of the global ocean–atmosphere–land system for prediction of seasonal and interannual variability?	Ants Leetmaa/Gordon Bonan
1130	LUNCH	
1300	Short Presentations, Open Discussion, and Charge to Working Groups—J. Shukla, Discussion Leader Speakers: —Kikuro Miyakoda —Peter Webster —Antonio Moura	

1400	Working Group Meetings
	1. Observations—David Halpern, Chair
	2. Empirical Studies—Mike Wallace, Chair
	3. Modeling—David Anderson and Edward Sarachik, Co-Chairs
1500	BREAK
1520	Resume Working Group Meetings in previously assigned breakout rooms
1630	Plenary Session—Keoni Auditorium Reports from Working Group Chairs
1700	RECESS
WEDNESDAY, MARCH 3, 1993	
0830	Plenary Session—Keoni Auditorium
0900	Working Group Meetings in previously assigned breakout rooms
1200	LUNCH
1300	Working Group Meetings, continued
1400	All Participants return to Keoni Auditorium
1400	Plenary Discussion
	Reports from Working Group Chairs
1500	BREAK
1520	
1600	Closing Remarks —Michael Ghil, Climate Research Committee —Jagadish Shukla, Conference Chair
1630	ADJOURN

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MARCH 1–3, 1993

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C

Acronyms and Other Initials

ACCP	Atlantic Climate Change Program
ADEOS	Advanced Earth Observing Satellite
AIRS	Aerometric Information Retrieval System
AIREP	Aircraft Enroute Report
AOML	Atlantic Oceanographic and Meteorological Laboratory
ARCS	Atmospheric Radiation and Cloud Station
ARM	Atmospheric Radiation Measurement program
ATSR	Along-Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
CART	Cloud and Radiation Testbed
CENR	Committee on Environment and Natural Resources
CLIVAR	Climate Variability and Predictability program
CNES	Centre National d'Etudes Spatiales (French National Center for Space Studies)
COADS	Comprehensive Ocean-Atmosphere Data Set
COARE	Coupled Ocean-Atmosphere Response Experiment
CRC	Climate Research Committee
DERF	dynamic extended-range forecasting
ECMWF	European Centre for Medium-Range Weather Forecasting
EMEX	Equatorial Mesoscale Experiment
ENSO	El Niño/Southern Oscillation
EOS	Earth Observing System
EOSDIS	Earth Observing System Data and Information System

EPOCS	Equatorial Pacific Ocean Climate Studies
ERS	Earth Remote Sensing Satellite
ESA	European Space Agency
FSU	Florida State University
GEOSAT	Geodetic satellite
GFO	GEOSAT follow-on
GAME	GEWEX Asia Monsoon Experiment
GARP	Global Atmospheric Research Program
GCIP	GEWEX Continental-scale International Project
GCM	general circulation model
GCOS	Global Climate Observing System
GEWEX	Global Energy and Water Cycle Experiment
GOALS	Global Ocean-Atmosphere-Land System
GOOS	Global Ocean Observing System
GTS	Global Telecommunication System
ICSU	International Council of Scientific Unions
IFREMER	Institut Français de Rechèrche pour l'Exploitation de la Mer
IOC	Intergovernmental Oceanographic Commission
IRICP	International Research Institute for Climate Prediction
ITCZ	Intertropical Convergence Zone
JGOFS	Joint Global Ocean Flux Study
MODIS-N	Moderate Resolution Imaging Spectrometer-Nadir
MSU	Microwave Sounding Unit
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NMC	National Meteorological Center
NOAA	National Oceanographic and Atmospheric Administration
NORPAX	North Pacific Experiment
NRC	National Research Council
NSCAT	NASA Scatterometer
OCTS	Ocean Color and Temperature Scanner
OLR	outgoing longwave radiation
PEQUOD	Pacific Equatorial Ocean Dynamics
PMEL	Pacific Marine Environmental Laboratory
SACZ	South Atlantic Convergence Zone
SAR	Synthetic Aperture Radar
SeaWiFS	Sea-Viewing, Wide Field-of-View Sensor
SEQUAL-FOCAL	Seasonal Equatorial Atlantic Experiment-Francais Ocean et Climat dans l'Atlantique Equatorial
SHEBA	Surface Heat and Energy Budget of the Arctic

SOI	Southern Oscillation Index
SPCZ	South Pacific Convergence Zone
SSMI	Special Sensor Microwave Imager
SST	sea-surface temperature
STORM	Storm-scale Operational and Research Meteorology
TAO	Tropical Atmosphere Ocean (array)
TIWE	Tropical Instability Wave Experiment
TOGA	Tropical Ocean and Global Atmosphere program
TOPEX	Ocean Surface Topography Experiment
TPFO	TOPEX/Poseidon Follow-On
T-POP	TOGA Program on Prediction
TRMM	Tropical Rainfall Measurement Mission
VISSR	Visible and Infrared Spin-Scan Radiometer
VOS	Volunteer Observing Ships
WCRP	World Climate Research Program
WEPOCS	Western Equatorial Pacific Ocean Circulation Studies
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment
WWW	World Weather Watch
XBT	Expendable Bathythermograph
ZC	Zebiak-Cane model

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