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A Scientific Plan

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PREFACE

The global system of earth, ocean, ice, and atmosphere that determines our climate is vast, complex, and infinitely challenging to science. In recent years, we have become increasingly interested in the fluctuations of climate on time scales of months, seasons, or several years. It has become clear that these involve not only the global atmosphere, but also the ocean--indeed the entire climate system. This report outlines a program of observations and research to advance our understanding of the most powerful family of atmospheric and oceanic variations on these time scales--those associated with the El Nino phenomenon and the Southern Oscillation (jointly referred to in this document as ENSO).

Study of phenomena such as these, spanning a major fraction of the globe and several years' duration, is clearly a formidable challenge, as well as an exciting opportunity. Thus, it is not surprising that the scientific planning for such an enterprise passes through a lengthy and complex gestation period. As the World Climate Research Program (WCRP) took shape in the late 1970s, prediction of seasonal and interannual climate fluctuations emerged as one of its major objectives. In June 1981, the Climate Research Committee (CRC)--which serves as the U.S. national scientific supporting body for the WCRP--reviewed a growing body of research pointing to connections between tropical ocean events and subsequent climate anomalies in midlatitudes. In July 1981 at Boulder, Colorado, the CRC organized an informal discussion group in conjunction with a meeting of scientists associated with the EPOCS (Equatorial Pacific Ocean Climate Studies) program. Based on this discussion, conceptual papers were drafted by T. Barnett and J. M. Wallace, both CRC members, with most welcome assistance from P. Julian of the National Center for Atmospheric Research (NCAR). Additional informal discussions among groups of meteorologists and oceanographers were held in September 1981 at NCAR and at the Scripps Institution of Oceanography in La Jolla, California.

In February 1982, the CRC reviewed the results of these discussions--results that had begun to assume the form of embryonic plans for a major multiyear field observational program in the Pacific. By this time, many interested scientists and research groups in both the academic community and in government had become entrained in this process of exploratory planning. Indeed, planners in the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation, and other agencies were already discussing the organizational and logistical challenges of such a program, which would form a logical extension of a number of highly successful Pacific-oriented U.S. research programs. Thus, a significant national constituency was growing. In order to elicit the contributions of this larger community to the evolving plan, the CRC organized a Study Conference at the Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey, in October 1982, at which the draft plans were intensively discussed and extensively revised. Subsequently, a follow-up workshop was convened in Miami, Florida, in May 1983 to discuss implementation possibilities.

The CRC also realized that a fully developed ENSO program would require the support and participation of other nations and would, moreover, be an important component of the international WCRP. Indeed, the Joint Scientific Committee for the WCRP rapidly seized on ENSO as a major building block for an even more comprehensive program to study the interannual variability of the Tropical Ocean and Global Atmosphere (TOGA). The Committee on Climatic Changes and the Ocean (CCCO), sponsored by the Intergovernmental Oceanographic Commission and the Scientific Committee on Oceanic Research as the oceanic counterpart to the Joint Scientific Committee, defined subprograms of TOGA in the Atlantic, Indian, and Pacific Oceans, the last of these meshing with U.S. ENSO aspirations. These programs were also discussed favorably at the well-attended Joint Organizing Committee/Scientific Committee on Oceanic Research Conference on Large-Scale Ocean Experiments in Tokyo in the spring of 1982. At this writing, an international TOGA steering committee has been formed, and a TOGA study conference is expected to be organized in the relatively near future.

A SCIENTIFIC PROSPECTUS

The vagaries of global climate seem at first glance random, almost chaotic. However, there is a strong signal that stands out above the otherwise noisy background of short-term climate change. This signal is loosely called the Southern Oscillation (SO). Traditionally, it has been regarded as primarily comprising a large-scale seesaw of atmospheric mass between the Pacific and Indian Oceans in the tropics and subtropics. The oscillation is irregular, but its preferred period lies in the range of two to seven years. Studies over several decades have shown that the SO actually involves a "family" of oceanic and atmospheric climatic fluctuations around the globe involving many regions of both northern and southern hemispheres and operating on both seasonal and interannual time scales. It is associated with interannual variations of the monsoon over India, shifts in the Intertropical Convergence Zone (ITCZ) and South Pacific Convergence Zone (SPCZ) over much of the equatorial Pacific Ocean, interannual variations of the monsoon over India, and "teleconnections" that link atmosphere and ocean conditions in the tropical Pacific to conditions in other parts of the tropics and to weather over North America and elsewhere. Related changes also occur in various other regions of the world's oceans. The most dramatic of these appears in the equatorial Pacific Ocean and is commonly termed El Nino (EN), an anomalously large warming of the coastal waters off South America, a phenomenon often damaging to the important local fishery industry. A brief description of the most recent such event, which ran its course during the development of this report, is presented in Appendix A.

The SO and related phenomena comprise the largest signal in short-term global climate variability. Because of the involvement of the ocean, the characteristic time scale of the phenomenon is long enough so that various elements of its early evolution may be useful in predicting subsequent changes in global climate. In the last few years, statistical relationships between various elements of the SO and North American climatic anomalies have been used as a basis for rudimentary seasonal climate prediction models (Barnett, 1981). The physical concepts behind these models are associated with the shifts in planetary wave systems noted above, which result in changes in the jet stream positions and hence changes in storm tracks, surface air temperature, precipitation, and other climatic variables.

The first predictive models (Barnett, 1981) have been purely statistical and have capitalized on the long time scale associated with SO phenomena, e.g., models to predict surface air temperature over North America several seasons in advance. Recent gains in explaining the dynamics of SO phenomena give hope that it may soon be possible to integrate physics into the forecast process to develop more reliable and skillful short-term climate prediction models.

The program described in this report is designed to investigate this promising possibility. Its goals are to describe and to seek an understanding of the mechanisms that control the SO, and to express this understanding in a hierarchy of models aimed ultimately at improving the prediction of short-term, regional climate changes over North America and other important agricultural regions.

1.1 THE SOUTHERN OSCILLATION FAMILY

Around the turn of the century scientists began documenting fragments of the SO phenomenon. However, it was left to Sir Gilbert Walker (Walker, 1923) to describe it as a "swaying of pressure on a big scale backwards and forwards between the Pacific and Indian Oceans. . . ." Differences in station pressures reflect this movement in mass and have been used to compute an "SO Index." Associated with this swaying of mass between the hemispheres are remarkable changes in wind, temperature, and rainfall in the monsoon regions, the central and western equatorial Pacific, and indeed throughout the tropics. While not simply periodic, the phenomenon is certainly a recurrent one, with the interval between events ranging from two to seven years. Huge changes in the equatorial[1] thermocline of the Pacific Ocean accompany these atmospheric events.

The global extent of the SO phenomenon can be illustrated by enumerating some further members of the SO family.

- El Nino is generally referred to as an anomalous warming of ocean water temperature off South America usually accompanied by heavy rainfall in the coastal regions of Peru and Chile. The resulting effect on the local fishery industry of Peru is often devastating. The warm sea surface temperatures extend in the east-west direction along the equator over a quarter of the earth's circumference. During such an event, the earth's thermal equator, which normally lies at about 7°N, moves southward toward the geographic equator. The ITCZ is closely coupled to the thermal equator and also moves southward and intensifies. Major changes of a similar nature occur in the SPCZ in the southern hemisphere. At the same time, the region of concentration of equatorial precipitation moves eastward from Indonesia to the dateline.
- Associated with the changes from "warm" to "cold" sea surface temperature anomalies and the rearrangement of the ITCZ, SPCZ, and other convective areas are major changes in the atmospheric tropical circulation. First investigated in the context of the EN and SO phenomena (Bjerknes, 1966), these changes include principally the zonal component of low- and high-tropospheric winds. The resulting circulation cell oriented in a vertical zonally-oriented plane was termed by Bjerknes the Walker circulation cell. A schematic version of the extremes in the position of the Walker cell is included in Figure 1. It has long

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[1] In this document, the term "equatorial" is used to refer to a narrow oceanic zone (approximately 5°N to 5°S) centered on the equator where the unique dynamics imposed by small values of the Coriolis parameter dominate. The term "tropical" refers to the larger conventional definition of the tropics, taken for convenience to be 30°S to 30°N.

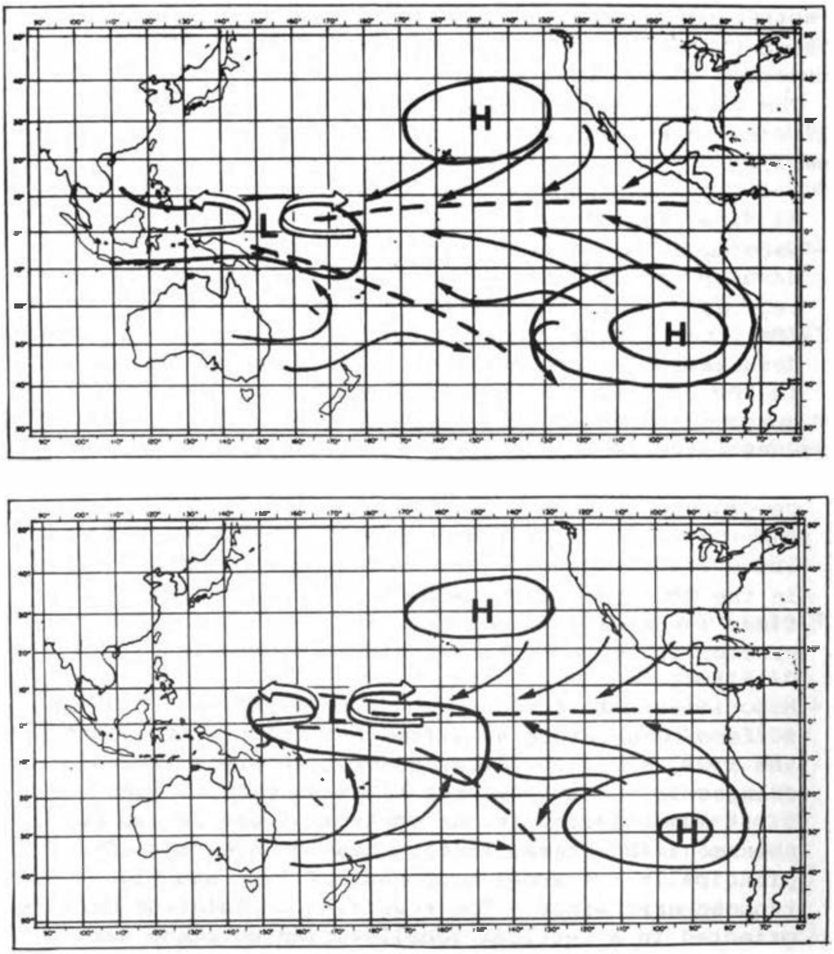

FIGURE 1. Schematic depiction of the two phases of the Southern Oscillation corresponding to the "cold-phase" or normal conditions (top) and the "warm phase" or El Nino conditions (bottom). Sea level pressure is shown by the solid contours and the surface wind flow by the solid arrows. The location of the Intertropical Convergence Zone (ITCZ) and South Pacific Convergence Zone (SPCZ) are indicated by the heavy dashed lines. The full arrows indicate the rising portion of the Walker Circulation.

been known that variations in the monsoon system over India cause great changes in the rainfall over that subcontinent, as well as the Indonesian maritime continent. As described in Sir Gilbert Walker's definition of the Southern Oscillation, the variations in pressure and rainfall in these regions appear to be closely related to the SO cycle. For example, there is a tendency for the EN events to precede relatively dry Indian monsoon seasons but to follow a weak winter monsoon.

- The connection in the atmosphere between the SO, EN, and the Walker Circulation in the tropics and associated changes in the high latitudes has recently been demonstrated both empirically and theoretically (Horel and Wallace, 1981; Hoskins and Karoly, 1981). This clearly suggests that perturbations in the pattern of atmospheric heating over the equatorial Pacific affect the planetary wave structure over much of the North Pacific Ocean, North America, and probably other parts of the globe. An example of the latter type of result is schematically shown in Figure 2. A number of studies have constructed forecast models that attempt to predict surface temperatures over North America using the empirical correlations between the SO and EN and subsequent seasonal temperature anomalies (Barnett, 1981; van Loon and Madden, 1981). Figure 3 portrays the pattern of potential predictability owing to the correlation field. This pattern closely matches the observed pattern of sea surface temperature anomalies during January and February 1983.

Because of its close relation with the atmosphere, the ocean appears to be a key element in stabilizing and/or driving the SO phenomenon. The ocean stores, rearranges, and gives up heat to fuel the atmospheric circulation system while the latter provides momentum to the ocean to help drive the ocean current systems and influences the fluxes of radiation and sensible/latent heat from the ocean surface. The physics and dynamics of this coupled system clearly provide a rich set of scientific problems.

Recent investigations show that the oceans and atmosphere communicate most effectively in the tropics, where the thermodynamic time scale of ocean response is comparable with the corresponding atmospheric time scales and the dynamic response of the oceanic mixed layer to the wind is stronger. At higher latitudes this ocean

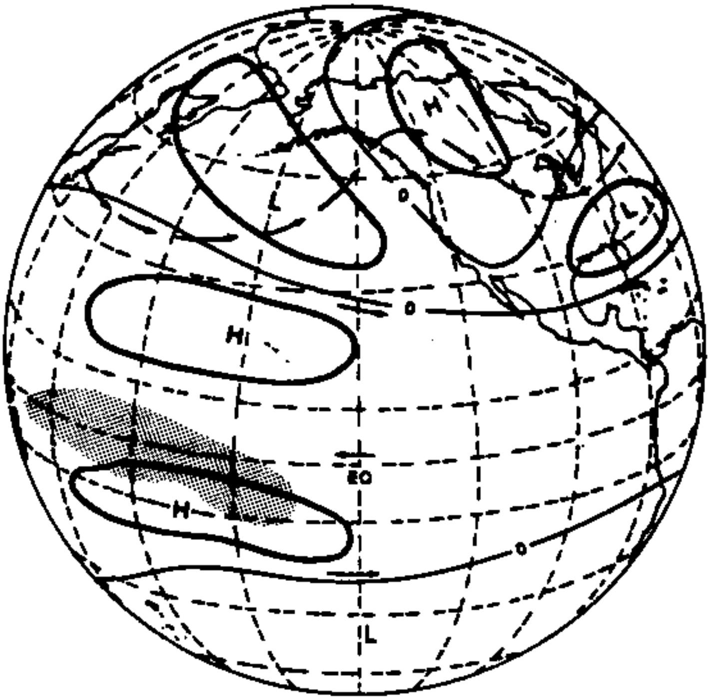

FIGURE 2. Schematic illustration of hypothesized global pattern of middle and upper tropospheric geopotential height anomalies during a northern hemisphere winter during an episode of warm sea surface temperatures in the equatorial Pacific. The heavy arrows reflect the strengthening of the subtropical jets in both hemispheres and stronger easterlies near the equator. The lighter arrows depict an actual streamline as distorted by the anomaly pattern, with pronounced troughing over the central North Pacific and ridging over western Canada. Shading indicates enhanced cloud and rain (from Horel and Wallace, 1981).

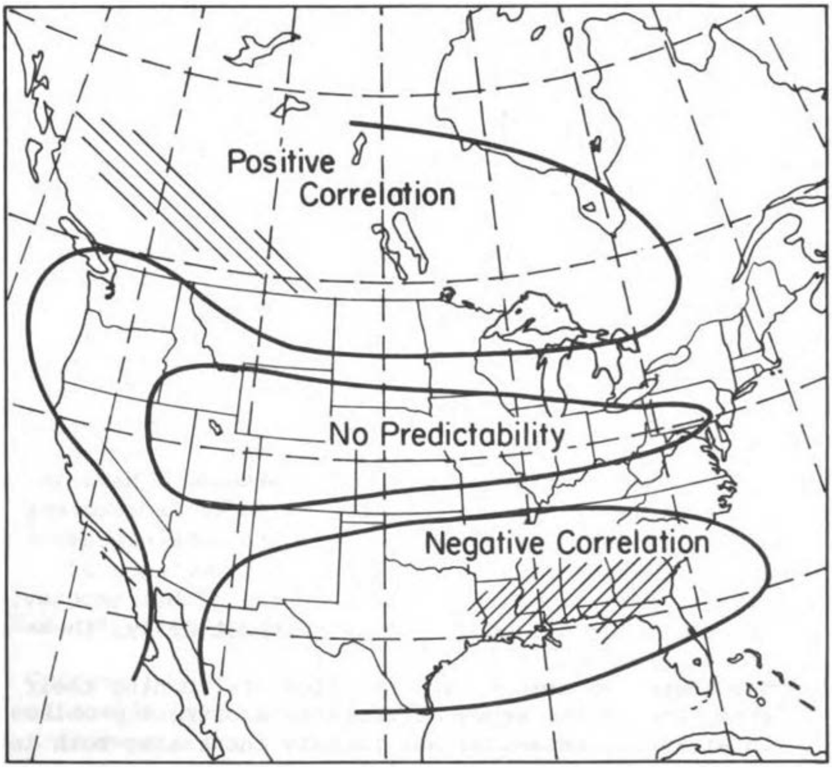

FIGURE 3. The general relationship between an objectively defined Southern Oscillation, El Nino index, and seasonal temperature anomalies over continental North America the following winter season. Positive and negative correlations of significant magnitude exist for the regions indicated and are particularly strong in the hatched areas. The region of no correlation and no predictability is also shown (after studies by Barnett, 1981; van Loon and Madden, 1981).

response is much more sluggish, effecting some degree of decoupling between the two media. Thus, it appears that a key to understanding the global fluctuations of climate associated with the SO lies in studying the interaction between the oceans and the atmosphere in the tropics. Present knowledge clearly indicates that this coupling is strongest in the equatorial Pacific Ocean. This is partially due to the huge size of the Pacific (whose time scales span several annual cycles) and also to the fact that the western Pacific experiences atmospheric forcing from both the monsoon and the trade wind systems, both key elements in the Southern Oscillation.

1.2 PROGRAM JUSTIFICATION

There are a number of compelling reasons for initiating a SO program now. They fall into three general classes, outlined below: scientific, practical, and organizational.

1.2.1 Scientific

- The cumulative studies of the SO phenomenon have in the last several years been pulled together into the first fragments of a theory for short-term global climatic variation. In view of the importance of climate variations to society and the global economy, it seems that we should pursue, without delay, these encouraging beginnings.
- The number of scientific investigators turning their attention to the study of short-term climate problems is already substantial and rapidly increasing both in the United States and abroad. The recent scientific results noted above give a sense of excitement and urgency to the field. Also, the recently organized World Climate Research Program (WCRP) offers excellent opportunity for an efficiently coordinated attack on the SO problem. The subject area is clearly one ripe with scientific opportunity.
- The SO can be investigated as an atmospheric and as an oceanographic problem separately. These simpler disciplinary problems appear tractable as observational and modeling studies, and they are likely to yield important, useful results in their own right, while simultaneously contributing to an understanding of the workings of the coupled atmospheric-oceanic system.

1.2.2 Practical

- There is little doubt that the world badly needs improved seasonal and interannual climate predictions. Society today makes heavy demands on vital resources such as water, food, and energy, and we must therefore effectively manage these resources to ensure our continuing welfare. Foreknowledge of major climatic variations (e.g., drought, severe winters) would be of great value in this effort. For example, in the winter of 1976-1977 heating oil supplies in the United States were virtually annihilated by severe and extended cold weather. Major features of that winter temperature pattern were predicted, but not in time nor with sufficient confidence to allow the necessary management decisions to be made. Recent research suggests that it may be possible to predict with useful skill such extremely cold winters several seasons in advance in certain regions of the United States (see Figure 3).
- Study of the SO phenomena also holds some promise of improving our ability to predict weather at medium ranges, i.e., seven to ten days. For example, there is evidence that cold air outbreaks over eastern Asia tend to be followed, within several days, by an enhancement of convective activity over parts of the tropical Pacific.

1.2.3 Organizational

- Current research efforts are attacking some subelements of the SO problem. However, the programs do not have a framework for coordination and overall management commensurate with the global nature of the problem they are addressing. Thus, it is not surprising to find that many important practical areas of scientific endeavor are not being addressed. The present plan is intended to help focus both current and future research on the SO problem to an efficient, satisfactory conclusion. It will also serve as a mechanism for engendering a vigorous international program required to address the global problem.
- Required observations are to a considerable extent either in hand or within our grasp. Ongoing observing programs such as the surface-based components of the World Weather Watch and the already-planned satellite

programs of India, Japan, and the United States will provide essential information. The observational and research programs of the past decade have left a rich legacy of capabilities. For example, the Global Weather Experiment demonstrated that buoys can provide valuable observations over large expanses of ocean at low cost. Thus, a SO program will not require de novo development of an expensive observing system.

1.3 SCIENTIFIC ISSUES

In order to make progress toward understanding the physics of the SO and using this knowledge to improve short-range climate predictability, it will be necessary to address an array of scientific issues, which can be grouped into three rather general categories:

- Issues that concern the atmospheric response to a prescribed sea surface temperature anomaly, irrespective of how the anomaly came about. Modeling studies indicate that the atmosphere adjusts to the presence of such an anomaly on a time scale of a week or two, in a manner dependent in part on the general character of the extratropical circulation.
- Issues that concern the response of the tropical ocean basin to a prescribed, time-dependent surface wind stress and air-sea energy exchange on time scales ranging from months to seasons.
- Issues that can be addressed only in the context of the coupled ocean-atmosphere system.

For each of these categories, we will briefly review existing knowledge, the work currently in progress, and the scientific problems that need to be addressed in future studies. Specific scientific objectives and research strategies for achieving them are discussed in later sections.

1.3.1 Atmospheric Response to a Prescribed Sea-Surface Temperature Anomaly

The fact that precipitation anomalies in the central equatorial Pacific persist for periods of a year or longer and are strongly correlated with sea-surface temperature anomalies on that time scale suggests that part of the low frequency variability of rainfall in this region may be viewed as a response to sea-surface temperature anomalies. However, the relationship also depends on the background mean sea surface temperatures and seems to be primarily a function of the total field. Consequently, the correlation between sea surface temperature and precipitation anomalies is not as strong in the eastern Pacific, where background temperatures are lower.

The atmosphere responds to regional changes in sea-surface temperatures through a complex sequence of processes involving vertical fluxes of heat and moisture by random molecular motions at the air-sea interface, turbulent fluxes within the planetary boundary layer, and deep cumulus convection through the depth of the equatorial troposphere. These processes have been the focus of a number of previous field experiments conducted in tropical oceanic regions. In the ENSO program, the emphasis is not on the fluxes themselves, but on the large-scale circulations that develop in response to the sea-surface temperature anomalies. To the extent that it is possible to monitor these fluxes by remote sensing via satellites and from marine surface observations, every effort will be made to do so. However, it is clear that, barring major breakthroughs in measurement techniques, it will not be possible to obtain direct observations of vertical fluxes over the entire equatorial Pacific, over a period long enough to sample several El Nino events. Hence, for purposes that require explicit knowledge of the fluxes, it will be necessary to infer them indirectly on the basis of the distribution of sea-surface temperature, surface wind, temperature and relative humidity, cloudiness, and rainfall, making use of such relationships as the bulk aerodynamic formulae.

As part of the readjustment in the tropical circulation and associated changes in heating, the low level wind convergence and upper level divergence fields change, thereby altering the generation of atmospheric vorticity and the forcing of large-scale atmospheric waves. The latter, known as Rossby waves, may propagate into higher latitudes and appear to be responsible for the observed teleconnection patterns.

In order to lay the groundwork for a quantitative specification of the atmospheric response to a prescribed, regional sea surface temperature anomaly, it will be necessary to extend our present knowledge and modeling capabilities in a number of areas. The related scientific questions can be grouped into three categories: (1) those that concern the local atmospheric response to a prescribed, regional sea surface temperature anomaly; (2) those that concern the remote, directly forced response; and (3) those that concern possible additional effects related to interactions with transient phenomena.

The Local Response. Both observational and modeling evidence suggests that, in a gross sense, the atmosphere responds to a changing pattern of sea-air heat fluxes in a thermally direct sense, so that deep cumulus convection tends to remain associated with the large-scale "hot spots" on the underlying ocean surface as they shift from one part of the tropical ocean to another. However, when one considers the observed association between equatorial convection and precipitation and the sea surface temperature pattern in some detail, there are some significant differences in space and time scales that are not well understood. Even when the sea surface temperature pattern is rather smooth on a regional scale, much of the observed convective precipitation over the equatorial Pacific tends to be concentrated in discrete mesoscale cloud bands: the ITCZ and SPCZ. Changes in the sea surface temperature field tend to shift the positions of these features and to change their intensity.

The general circulation models that have been used thus far for the investigation of these phenomena do not have enough spatial resolution to simulate the mesoscale structure in the precipitation field and, therefore, it is not yet known whether the present model parameterizations of boundary layer and mesoscale processes are sufficiently accurate for estimating the local atmospheric response to equatorial sea-air flux anomalies.

The response in the precipitation field, through latent heating of the atmosphere, ultimately determines the remote climatic response at higher latitudes. The sensitivity of climatic fluctuations over North America to the detailed structure of local response has yet to be determined; dynamical considerations would suggest that minor shifts in the position of features such as the ITCZ may be less important than changes in the amount of precipitation occurring on larger scales. In any case, it is clear that an improved understanding of the local response to a prescribed sea surface temperature anomaly is a prerequisite for improved climate prediction in the equatorial belt and for quantitative estimates of the remote response at higher latitudes.

An understanding of the local response in the surface wind field is also an essential part of any complete theory of the SO. The ocean is capable of responding to rather small-scale features in the pattern of surface wind stress in the equatorial belt. A resolution of this structure will require additional observations in this belt, as described in Chapter 2. Further investigation of the near-equatorial surface wind field will also require experimentation using models with high horizontal resolution and careful treatment of atmospheric planetary boundary layer processes.

The Remote Response. By setting up anomalous forcing of the atmosphere through changes in precipitation and release of latent heat, tropical sea surface temperature anomalies are capable of altering atmospheric planetary wave patterns both at extratropical latitudes and in other parts of the tropics. For example, a deepening of the Aleutian low is associated with warm episodes in the equatorial Pacific.

Recent developments in the theory of forced planetary waves on a sphere provide a basis for understanding the extratropical response to equatorial sea surface temperature anomalies (for example, see Hoskins and Karoly, 1981; Webster, 1981). In the present stage of development, the theory is helpful in interpreting the shape, vertical structure, and seasonal dependence of the observed response over the Pacific and North America, but it does not explain why some warm episodes in the equatorial Pacific, such as the 1976-1977 event, produce a large response over North America, while others, such as the 1972-1973 event, produce a rather different response. Obviously, an understanding of individual events is a prerequisite for a strong predictive capability.

The remote response in other parts of the tropics and subtropics is also of considerable practical importance, since many of the agricultural regions within this belt are subject to recurrent drought episodes that have far-reaching and sometimes tragic implications. There is some observational evidence of a weak but statistically significant SO "signal" in rainfall statistics throughout much of the tropics. It is possible that this signal is weak because it is obscured by other, unrelated, more local phenomena; in that case, the prospects for prediction of droughts are not very good. On the other hand, it is also possible that a stronger, potentially useful signal exists and that it might be resolved by further empirical studies based on guidance provided by the types of theoretical studies described above.

Interactions With Transient Phenomena. Much of the discussion in the previous two subsections is based on the notion of an equilibrium, steady state atmospheric response to a prescribed equatorial sea surface temperature anomaly. It is also possible that the same sea surface temperature anomalies produce changes in certain statistics of the high frequency transient fluctuations that we associate with "weather." For example, the deepening of the Aleutian low in association with warm episodes in the equatorial Pacific noted above is associated with a southward shift in the "stormtrack" across the western and central Pacific. There is also a possibility of significant changes in the frequency of "blocking" events over certain parts of the hemisphere, in the frequency or tracks of hurricanes, or in the timing of seasonal events such as the onset of the monsoon. Many of these questions can be readily addressed in coordinated series of experiments with general circulation models.

1.3.2 Ocean Response to Atmospheric Forcing

The strongest oceanic climate signal associated with the SO occurs in the tropical Pacific. The signal manifests itself as large changes in the east-west slope of sea level across the basin, alterations of the Equatorial Current Systems, and associated changes in thermocline depth over much of the ocean. But the single most important climate-related oceanographic phenomenon in the tropical Pacific is the generation, persistence, and decay of sea surface temperature (SST) anomalies. As noted in the beginning of this chapter, these anomalies develop over a period of months and persist for a year or longer (Rasmusson and Carpenter, 1982). They often are not associated with changes in the local wind (although the currents are, of course, wind-driven), but rather with large changes in the depth of the thermocline. For example, during EN SST increases as the thermocline deepens by 50-100 m off the coast of Peru even though the along-shore winds remain favorable to upwelling (Enfield, 1980).

The purely oceanic component of this study is designed to gain understanding of the dynamics and thermodynamics of these anomalies. This will require study of the various elements of the oceanic heat budget, a difficult task considering the different processes that appear important. The SST anomalies are not only affected by local processes (thermodynamics of mixed layer; response to local wind fields), but also by remote processes (advections; propagation of equatorially trapped, internal waves generated in remote regions). They are, therefore, only the surface expressions of much more fundamental events and processes in the ocean. The problem is rendered more complicated by the fact that the physical processes important to the heat budget in one geographic region of the Pacific may not be important in another area.

The principal scientific issues associated with regional equatorial heat budget problems are discussed briefly below.

Eastern Tropical Pacific. The eastern tropical Pacific can be characterized by three geographic subregions that interact strongly during EN events. The heat balance of each of these subregions appears to be governed by a slightly different set of physical processes. The interactions, key processes, and what needs to be known about them are discussed below.

- A tongue of cool water extends from the Galapagos Islands (~90°W) to the dateline along the equator. It exhibits a rather regular annual cycle, but it is also the area where the largest SST anomalies occur during the EN occurrences. The tongue is probably produced by horizontal advection of cool water from the waters off Peru and by equatorial upwelling, both of which vary seasonally and interannually in response to the winds (Philander and Pacanowski, 1981). The relative contribution of these two processes is unknown, not only in the annual mean, but also in the annual cycle and in particular during anomalous events.
- The area south of the Galapagos Islands and extending to the coastal upwelling regions off Peru is one of the least known in the entire tropical Pacific, although it forms the important link between the Peru upwelling area and the cool tongue. During anomalously cold epochs, the tongue is definitely connected to the Peruvian upwelling as part of the South Pacific gyre circulation, and upwelling is also strong. Each year, during the southern summer, this connection seems to

be interrupted by warmer water in the vicinity of the Galapagos Islands and at the coast. This effect might be due to a seasonal weakening of the gyre circulation. During large SO events the weakening or displacement of the circulation appears to be a major contributor to the warming.

- The Galapagos Front stretches from the coast of Ecuador near 5°S toward the Galapagos Islands and continues westward, slowly losing strength. It is a very strongly developed boundary between the warm, low salinity water of the eastern tropical Pacific in the north and the cool waters of higher salinity coming from the Peru current in the south. The frontal dynamics consist of the usually southerly winds between the coast and the Galapagos Islands balancing a southward-directed oceanic pressure gradient. When the winds decrease, the water north of the front can overflow the cooler waters south of it and form a thin layer of warm water. While this general situation is well known, the details of the response are unclear, especially whether it is an annual event, amplified only during EN, or whether the situation during EN is of an entirely different nature. The dynamics of overflow need to be studied, since they have bearings on the formation of the SST anomalies in the critical region south of the Galapagos Islands.

Central Pacific. Surface heat input, changes in the currents and in upwelling (caused by changes in the winds) are possible causes of the observed temperature changes in the Central Pacific (see Figure 4). A quantitative assessment of the magnitude of these processes would lead to an understanding of the formation of the large surface temperature anomalies in this area and of their spreading.

A key component of the central ocean heat balance is wind-induced equatorial upwelling. Divergent Ekman flow in the surface layer and convergent geostrophic flow in the subsurface layer produce a circulation in the meridional plane, which leads to upwelling. Using this basin balance, equatorial upwelling in the Pacific has been estimated as $50 \times 10^6 m^3/sec$, a value comparable to the strongest ocean currents. The meridional circulation associated with equatorial upwelling and with the equatorial undercurrent also needs to be measured to study its response to wind fluctuations and to verify existing model computations. A quantitative under-

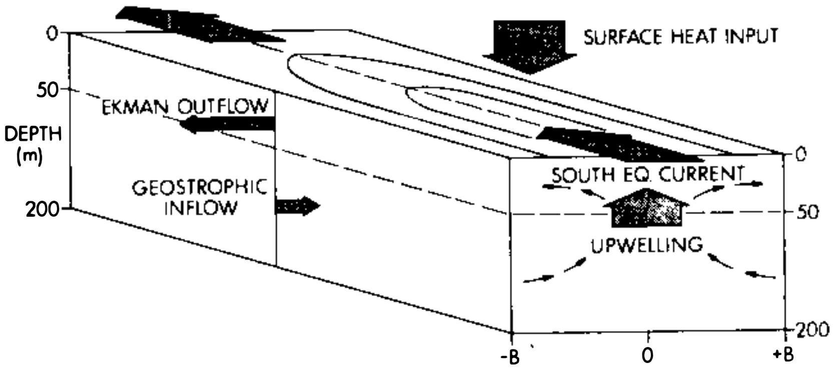

FIGURE 4. Schematic of the processes that contribute to the spatial and temporal evolution of a cold water tongue in the equatorial Pacific (from Wyrtki, 1981).

standing of the upwelling process is needed to assess its contribution to the cool tongue and to the development of anomalous temperature conditions.

Equally important processes involve the maintenance of the tropical mixed layer and the magnitude of the coupling between the mixed layer and the deeper ocean. It is important to understand the way in which the SST pattern is set up by the interaction of mixed layer processes with strong upwelling, vertical diffusion, and horizontal temperature advection.

Western Pacific. The upper layers of the western Pacific contain the greatest amount of heat per unit mass of any part of the world's oceans (except for several small regions of the Mediterranean, Red Sea, etc.). Thus, it has tremendous thermal inertia to help stabilize the ocean-atmosphere system. It also has the potential to release large quantities of both thermal and potential energy that might be important to distant ocean areas and the overlying atmosphere. While the surface temperature in this region appears to be less variable than in the eastern Pacific, the subsurface temperature (for example, the heat content of the mixed layer) shows large fluctuations that are well related to the SO.

1.3.3 Ocean-Atmosphere Interaction--The Coupled Problem

The key to understanding the SO appears to lie in a detailed knowledge of the physical processes that couple the tropical ocean and atmosphere. The importance and intimacy of this interaction has been alluded to above and at the beginning of this chapter. In particular, we have noted above that the EN sequence of events appears to be initiated by changes in the atmospheric forcing by the wind field, implying that something has already brought about a change in the atmospheric circulation. Further, we have noted that the spread and development of SST anomalies into the central Pacific are likely to result in modification of the atmospheric circulation, with teleconnections to higher latitudes. The separation of the latter effect from the normal atmospheric dynamics will be a difficult task that can probably be achieved only with models that faithfully reproduce both the basic state and transient phenomena.

Some of the key scientific issues associated with understanding the "coupled problem" are:

- What triggers the whole sequence of events connected with an episode of warm SST in the first place? It has been noted that a weakening of the South Pacific High apparently precedes the other events in the cycle, but we can only speculate (see below) why that weakening occurs in the first place. We do not yet have even a speculation as to why the next discernible change, the equatorial and eastward shift in the SPCZ and the eastward shift of the Indonesian Low into the Pacific, should occur. Alternatively, the trigger may lie in the interannual variations in the monsoon system and its interaction with the tropical ocean, thus confining the initiation to the tropics.
- What sets the time scale of the SO? There is an EN event and a concurrent peak in the SO every four to five years on the average, but the spectrum is broad near this peak, with individual events spaced as close together as two years and as far apart as ten years. At present there is no testable, plausible hypothesis for the triggering or the timing, but two broad conceptual frameworks have been suggested. They might be termed the random and the quasi-periodic.

  The random hypothesis suggests that the EN sequence is triggered when some stochastic fluctuation of the ocean-atmosphere system occurs in the proper conjunction, or at just the right time in relation to the annual cycle. One idea of this type suggests that a properly timed, but random, migration of the powerful Indonesian Low into the western Pacific will act as a trigger. Another suggests that the changes in the South Pacific High, which appear to lead and trigger all other changes in the tropics, are merely random fluctuations. A number of other possibilities of this kind have been suggested (e.g., waves in the Antarctic Circumpolar Current, convective overturning near the subtropical oceanic front). The random hypothesis explains the two-to-ten year time scale as a consequence of the stochastic nature of the forcing: since the cycle takes two years to work through, it cannot reoccur more often than every two years; how much longer it will take is a matter of chance.

The quasi-periodic hypothesis maintains that the aftermath of an EN sows the seeds for the next one: that all of the SO cycles are part of a connected chain of events. In the quasi-periodic hypothesis the ocean plays a key role because the atmosphere appears to have too little inertia--too short a memory--to sustain an oscillation with a period of up to five years.[2] There is no difficulty in finding oceanic processes that involve such long time scales. A (lowest mode baroclinic) Rossby wave takes approximately seven months to cross the Pacific at the equator; by 15°N the crossing time has increased to about two years, and by 30°N it is nine years. Such a wave feature, spawned by one event, may be the trigger for the subsequent event. Recent numerical model results lend some credence to the possibility of such a mechanism.

- Why do most, but not all, El Nino events set in early in the calendar year, with the maximum warm anomaly at the coast occurring a few months after the normal

[2] The quasi-biennial oscillation (QBO) in the equatorial stratospheric winds is an exception, demonstrating that a purely atmospheric mechanism cannot be entirely ruled out. However, the QBO is a largely stratospheric phenomenon that is governed by very different dynamical interactions from those governing the SO.

February SST maximum? Does it offer any clues to the nature of the coupling between the atmosphere and ocean? Then there are occurrences of an EN at an unexpected time of the year (e.g., 1930) or durations longer than the typical two-year cycle (1976-1980). Good case-by-case descriptions of the typical events, the "mavericks," and, perhaps as important, the "normal" progression of the seasonal cycle are badly needed.

- How is the ENSO signal transmitted from the western Pacific, where the weakening of the trade winds takes place, to the South American coast, where the most dramatic changes in the depths of the thermocline are observed? It has been suggested that an oceanic equatorial Kelvin wave is generated in the west, propagates eastward, and causes the observed thermocline displacement at the coast of South America (McCreary, 1976; Hurlburt et al., 1976). The theory is unambiguous and the observed structure and timing of the coastal changes are as expected. Nevertheless, there is not yet consistent observational evidence suggesting a sea level or SST signal propagating eastward across the central Pacific. For some EN events, we are nearly in the situation of having the signal leaving and arriving, but see no trace of its transit.
- How do events in the tropical ocean and atmosphere communicate and interact with midlatitudes? Present knowledge in this area is limited. For example, there are changes in the midlatitude Pacific SST patterns that follow an EN event, and it has been suggested that the midlatitude anomaly pattern will alter the weather over North America. The evidence from theory and numerical experiments supports the idea that the tropical SST anomalies are the important ones, but it is quite possible that the midlatitude SST anomalies play a role, especially if the standing waves generated by the tropical anomalies interact significantly with midlatitude transients.

  The midlatitude SST anomalies appear too soon after the equatorial ones for it to be likely that they are generated entirely by oceanic processes. It is quite possible that tropical SST anomalies alter the midlatitude atmospheric circulation, which then induces the midlatitude ocean anomalies. Current explanations for this coupling are not well defined and are the subject of considerable scientific debate.

In summary, there has been relatively little theoretical work that considers the atmosphere and ocean as a coupled problem. It is clear that some aspects of the SO phenomena are ripe for such an approach, while others will require a great leap of imagination. As always, imagination will be aided enormously by further data studies. The discussion points to a number of studies that could be carried out with the existing data base, but there are other questions that cannot be answered until that data base is enhanced notably by global, synoptic fields of surface wind, pressure, and SST.

1.4 CLIMATE PREDICTION

We have seen that certain elements of the SO family have life cycles of a year or longer, e.g., the tropical SST anomalies. It also seems evident that there is a reasonably strong linkage between these events and subsequent events at midlatitude, particularly over the north Pacific Ocean and North America. These presumed linkages already have been used to develop short-term climate forecast models.

The current forecast models are largely empirical. They capitalize on the facts that usually EN events: (1) are well developed during the northern summer, (2) will persist into the subsequent winter, and (3) are often associated with companion ocean temperature anomalies at midlatitude. Knowing that the communication between the tropics and high latitudes is strongest during the cool seasons, the models then use various statistical techniques to forecast cool season conditions over North America from antecedent (e.g., summer) ocean conditions. Figure 3 is one example of the current forecast skill attained by such models. It seems likely that this approach to forecasting will be explored in-depth over the next five to ten years as more information on the lead-lag structure of the SO phenomenon becomes available. The establishment of Experimental Climate Forecast Centers under the National Climate Program should accelerate this development and serve as a practical focal point for many of the results of the SO study.

The statistical models do not generally include any physics or dynamics and this is, perhaps, their major shortcoming. As elements of the SO dynamics are uncovered, they will need to be incorporated into the forecast models. Gradual resolution of key scientific issues noted above will open the way for the incorporation of this combination of statistics and dynamics into a new class of climate prediction model. The inclusion of dynamics offers the promise of improving accuracy, forecast range, and, perhaps most important, reliability. A major problem is to determine how this should be done (see below). It should be emphasized that these anticipated benefits will be closely linked to the rate of progress on the scientific issues raised above.

The issues of highest scientific priority in the area of predictability are:

- What levels of climate predictability might we ultimately expect to achieve? How do these estimates depend on geographical location, season, etc.? For instance, current statistical models show little or no forecast skill for temperature in the central regions of the United States. Is this a real feature of the climate variations in this region? Or, more likely, the result of an inadequate model? The answers to such questions are crucial to the development of forecasting models and to the direction of the scientific research called for above. For instance, for certain aspects of climate variability, a statistical-dynamical forecast modeling approach might be more appropriate than a totally deterministic forecast model.
- A sound, quantitative description of the evolution of ocean-atmosphere events in the global SO cycle is required. It is this sequence, with its inherent lead-lag relations, that useful forecast models must ultimately reproduce. These models must also be able to reproduce the observed differences between SO events and their midlatitude consequences--e.g., the 1972-1973 event was associated with relatively mild winter conditions over the eastern two-thirds of North America while the 1976-1977 event produced an extremely cold winter.
- Substantial theoretical effort is required to discover how to blend statistical relationships and dynamics optimally into a unified forecast model. Both points of view have their strengths and weaknesses. Indeed, most current climate models are built exclusively on one or the other approach. Our current understanding of the climate problem suggests that significantly

improved climate predictions will require the best of both approaches. Work now under way on how to combine these complementary approaches toward the forecast problem is only at a rudimentary stage.

- Forecast models for lead time of one-to-two seasons, no matter what their nature, will ultimately need to cope with the coupled ocean-atmosphere system. The strong interaction between these two fluids, together with the fact that the upper ocean can change significantly over the one-to-two season time scale, suggests that the use of a "static" ocean, permissible in short-range weather forecasting, will be inadequate for climate prediction.

1.5 STRATEGY AND GENERAL OBJECTIVES

We have described above the character of the SO and its crucial role in developing a physical basis for understanding and predicting global climate change. Our current knowledge also allows us to define clearly a scientific program that will address the following objectives.

- To develop an improved understanding of the *in situ* and remote atmospheric forcing of and response to fluctuations in equatorial Pacific SST anomalies;
- To identify the processes that control the development and time evolution of the thermal anomalies associated with the SO and EN in the equatorial Pacific Ocean; and
- To understand the large-scale ocean-atmosphere interactions responsible for much of the short-term interannual fluctuations of the coupled climate system and to determine the predictability of the system. Of particular interest are relationships between the SO phenomena and (1) climate fluctuations in midlatitudes, particularly North America, and (2) interannual variations in the Asian monsoon, including both its regional characteristics and its relationship to the planetary circulation.

In addition to the scientific objectives listed above, the program also includes the following, more operationally oriented objectives:

- The development of improved schemes for prediction of short-term climate variability and

- Design of the optimum operational observing system required to provide the data base for such predictions.

There already exists an impressive array of resources that provide a basis for studies of the SO:

- A near-global atmospheric observing system (the World Weather Watch) operated on a routine basis at no direct cost to the scientific community.
- An in-place skeleton ocean observing system over approximately half of the tropical Pacific, consisting of island sea-level observing stations and Expendable Bathythermographs (XBTs) from ships-of-opportunity.
- An extensive collection of historical data from ships, islands, etc., that allow us to define and study past behavior of the SO.
- Analyses of synoptic observations and other by-products of operational weather forecasting.
- A set of atmospheric and oceanic models that have successfully simulated some features of the SO family.
- A set of hypotheses, or at least chronologies, based on both data and theory describing some of the key features of the SO and how they evolve in time.

The scope and time scale of the SO phenomena itself and the scientific studies sketched briefly above dictate a program of decadal length. Our understanding of the phenomenon suggests that ocean-atmosphere interactions in the tropical Pacific and subsequent "teleconnections" to other parts of the globe, particularly North America, should be emphasized. The latter are among the strongest and best understood aspects of the SO, and seem to have the most immediate payoff in terms of short-term climate prediction. The regional focus defines a logistically feasible, geographically fixed set of observational problems. Indeed, considerable scientific interest already exists in tropical Pacific investigation and many program elements are already in place; however no coherent overall scientific framework has been established. The size of the region and the strong interest of many neighboring countries in climatic fluctuations imply that the program should ultimately be incorporated as an element of the World Climate Research Program.

2

THE PROGRAM PLAN

The El Nino/Southern Oscillation (ENSO) scientific program has three major components.

(1) An observational effort to:
   (a) monitor atmosphere-ocean interactions associated with the ENSO phenomenon over a period of a decade;
   (b) provide a more detailed description of a fairly representative El Nino (EN) episode spanning a 15-18 month period; and
   (c) provide detailed information concerning the processes that control the sea-surface temperature and the fluxes at the atmosphere/ocean surface.

(2) The upgrading and analysis of historical data sets that provide a partial description of the ENSO phenomenon during the past 30 years and more limited but nonetheless valuable information concerning its behavior over the past century.

(3) A modeling effort devoted to testing hypotheses concerning atmosphere-ocean interactions relevant to the ENSO phenomenon and to developing a predictive capability.

The observational effort is described from oceanographic and meteorological perspectives in the next two sections, followed by sections describing the work related to historical data sets and the modeling effort. Chapter 3 deals with management considerations: data management, relationship to existing programs, and coordination with international programs.

2.1 OBSERVATIONS: AN OCEANOGRAPHIC PERSPECTIVE

This section describes in somewhat greater detail the observations required in order to address the oceanographic questions relevant to the ENSO phenomenon. It is divided into three subsections.

2.1.1 lists the observations required for monitoring atmosphere-ocean interactions in the tropical Pacific, with emphasis on those fields that are essential for documenting oceanographic aspects of the ENSO phenomenon. The monitoring effort encompasses fluctuations on time scales ranging from weeks to years and includes as one of its objectives a more detailed determination of the climatological mean annual cycle. Major emphasis is on phenomena with large space scales, and therefore the monitoring network is thin but broad enough to encompass the entire Pacific basin. The monitoring activity is planned to extend through the full ten-year duration of the ENSO program.

2.1.2 describes a more intensive observational effort designed to be carried out in connection with one single EN event. It will commence several months before sea-surface temperature rises along the South American coast are expected to begin, and it will continue for 15-18 months. Since the special observations will be initiated with short lead time, in response to an early warning of an impending event, this component of the ENSO program is referred to as the EN Rapid Response Project.

Neither the monitoring effort nor the EN Rapid Response Project directly addresses the major gaps in existing knowledge of how the large sea-surface temperature anomalies and the associated anomalies in air-sea energy exchanges are created over a period of just a few months and sustained for a year or longer. For this purpose a set of three regional, process-oriented experiments, described in 2.1.3, will be carried out. In order to minimize competition for ships and other resources, these experiments will be carried out sequentially during the ten-year ENSO program, with little or no overlap between them. Each experiment will be designed so as to take maximum possible advantage of the background monitoring network described in 2.1.1.

There is considerable overlap between the observational requirements for the oceanographic part of the ENSO program described in this section and those for the meteorological part described in section 2.2.

2.1.1 Pacific Basin Monitoring

The objective of the Pacific Basin monitoring effort during the next decade is to describe the large scale aspects of the ENSO phenomenon in the tropical Pacific Ocean. The program must be designed to document all major large-scale changes in ocean circulation, heat storage, heat exchange, and wind forcing during the ten-year period. The monitoring program encompasses the following elements:

- The wind field, which is the driving force for the ocean circulation, will be estimated on the basis of observations from ships and islands, together with low level cloud motion vectors. A satellite-borne scatterometer would provide complete areal coverage.
- The thermal structure, which determines the heat content and the baroclinic component of the geostrophic flow, will be documented on the basis of XBT sections from ships of opportunity and research ships, and data from drifting buoys with thermistor chains.
- Sea surface topography, which is needed for documenting sea-level changes and for inferring the barotropic component of the ocean circulation, will be monitored using the existing network of sea level stations, augmented by a few additional stations in regions of special importance. An altimetric satellite would provide uniform coverage over important data-sparse regions.
- Sea surface temperature, which serves as an indicator of oceanic heat storage and is required as a lower boundary condition for atmospheric models, will be mapped on the basis of data from ships of opportunity and satellites. The collection of ship weather reports needs to be improved, and the quality of satellite-derived sea surface temperatures needs to be carefully determined.

It will be necessary to monitor winds, surface temperatures, and thermal structure in dynamically important regions not covered by shipping routes. For this purpose fixed buoys are needed in the core region of the southeast trade winds in the vicinity of 20°S, 85°W and 10°S, 105°W (see Figure 5). Since the equatorial

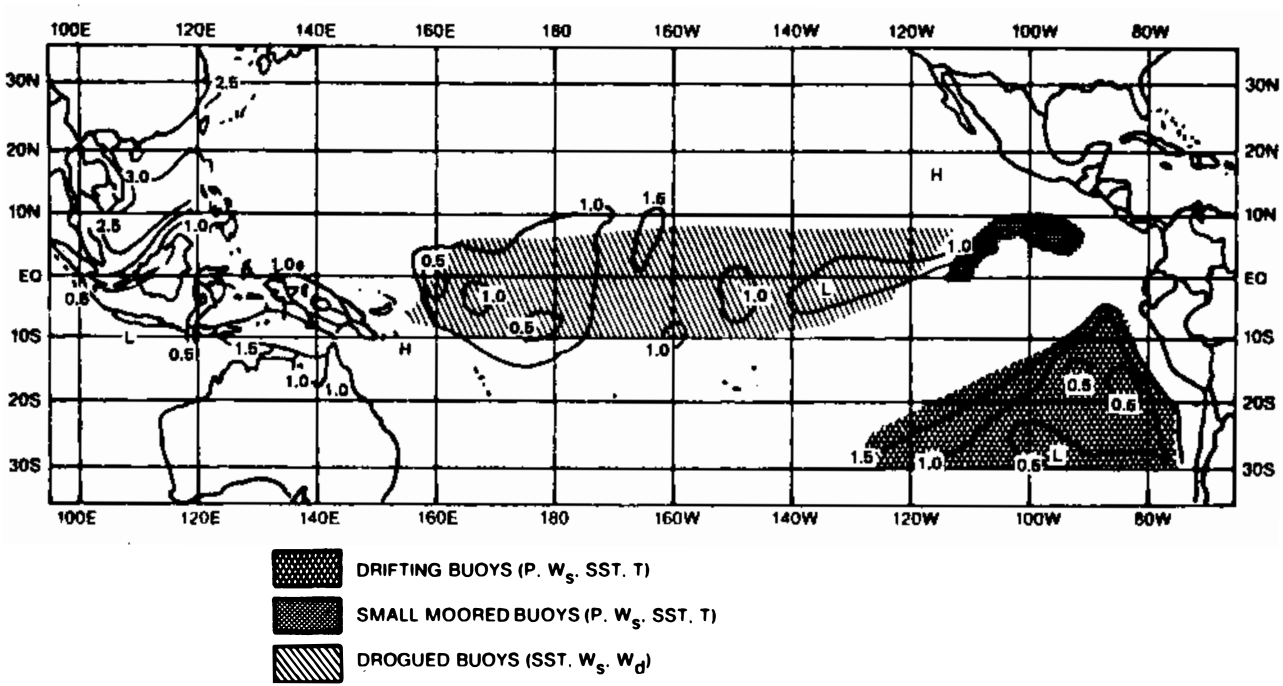

FIGURE 5. Composite map showing the density distribution of ship-of-opportunity meteorological reports (logarithmic scale) and the location of proposed buoy deployment to augment the ship reports.

undercurrent cannot be monitored by indirect methods, moorings at appropriate longitudes need to be maintained during the entire experiment to monitor this important component of the ocean circulation.

2.1.2 The El Nino Rapid Response Project

The continuing basin-wide observations listed in the previous subsection will yield data that can be used to identify the potential for the occurrence of a strong swing in the indices of the Southern Oscillation (SO) and the initiation of an EN event. A scientific team will be established to monitor and predict oceanic conditions associated with the occurrence of EN, thereby providing a basis for signaling a tentative start-up of the Rapid Response Project. The prediction methods will include both statistical and dynamical models with experimental predictions being made and verified at regular intervals. The full implementation of the project will await verification that the event has begun.

The El Nino Rapid Response Project will be instituted in two phases.

Phase I: A detailed operational plan will be developed. A preliminary plan is already in hand, but it will need to be revised based on (a) the strong, somewhat unusual 1982 EN event and (b) forthcoming information concerning the array of instruments that will actually be deployed in the Pacific-wide monitoring effort described above.

Phase II: The rapid response project will be instituted based on the forecast of an incipient El Nino event. The elements of this action can be conceptualized based on preliminary planning conducted to date. The essential observing systems that could be employed are illustrated schematically in Figure 6. They include: Current meter moorings deployed to fill in the long term current monitoring array; hydrographic cruises in key areas; aircraft flights to augment mapping the thermal structure with AXBTs. These aircraft will also be available for meteorological missions. Satellite-tracked drifting buoys would augment the current measuring arrays and the mapping of the upper ocean thermal structure.

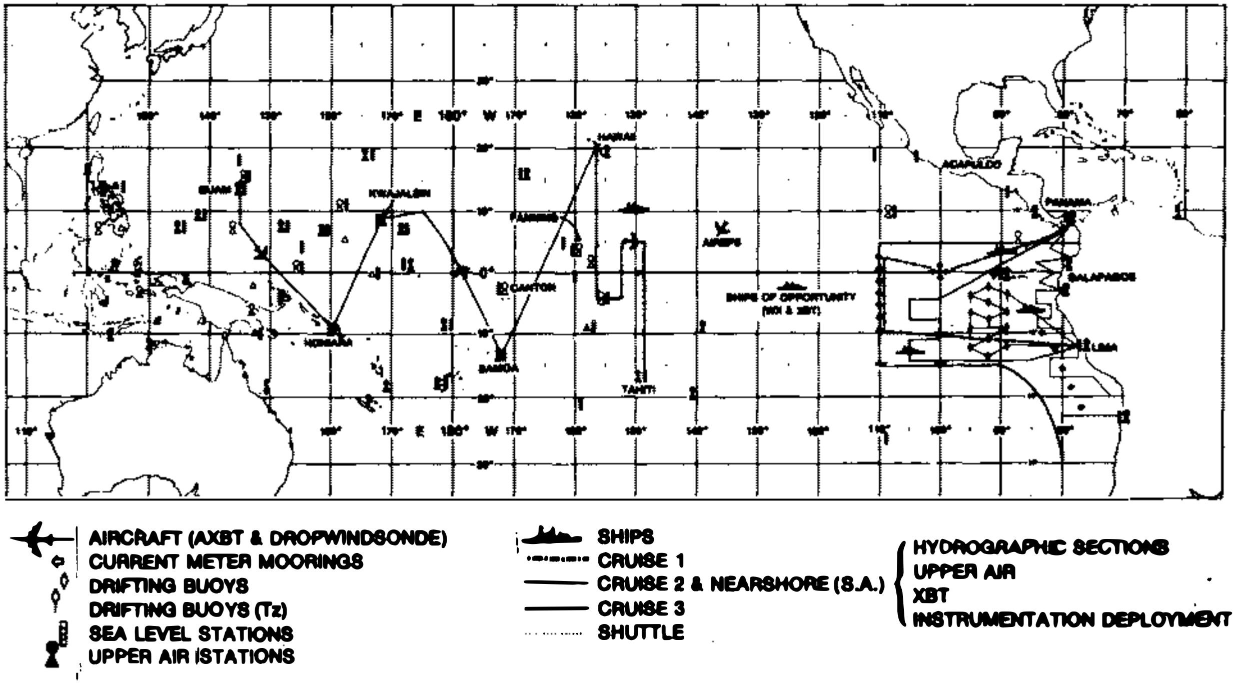

FIGURE 6. Schematic depiction of possible observing systems deployment for the El Nino Rapid Response Project. Phase 1: winds, sea level, sea surface temperature; Phases 2, 3, and 4: currents, sea level, sea surface temperature, subsurface temperature, biological-chemical samples, winds.

2.1.3 Process Experiments

Elucidation of the essential physical processes responsible for the observed sea-surface temperature and sea-level changes in various regions of the equatorial Pacific will require a number of specific process experiments. Since it now appears that the dynamics and thermodynamics of the mixed layer exhibit large regional differences, separate studies are planned for the eastern, central, and western ocean.

Eastern Pacific Program. The eastern Pacific is characterized by a shallow mixed layer and strong horizontal contrasts in sea-surface temperature. Studies of SST variability in this region have tended to focus on the interaction of the ocean circulation with the coastal boundary and the large-scale movement of water masses along and across the equator during EN events. An intensive field program has been in progress since 1979 as a result of cooperative efforts between National Oceanic and Atmospheric Administration (NOAA) scientists funded by the Equatorial Pacific Ocean Climate Studies (EPOCS) program and scientists at Oregon State University. Although the intensive measurements were concluded in early 1983, certain sea-level stations should be maintained, and XBT sections and drifter releases should be scheduled to continue at regular intervals as part of the basin-wide monitoring program described in 2.1.1. The analysis of observations taken during the intensive field phase is an essential part of the ENSO research program.

Central Pacific Program. The central Pacific program is concerned with sea-surface temperature changes over a broad expanse of ocean where the thermocline is too deep to directly interact with the surface waters and where horizontal gradients are weaker than in the eastern Pacific. Hence, it is not anticipated that the rather straightforward descriptive approach employed in the eastern Pacific program will be adequate for determining the nature and causes of sea surface temperature (SST) variability in the central Pacific. Thus, a rather different kind of program is envisioned. The proposed program is organized around the heat budget of the mixed layer (see section 1.3.2) with emphasis on those processes that contribute to the variability of SST. It may be viewed as an outgrowth or expansion of the Tropic Heat

Program sponsored by the National Science Foundation (NSF).

The principal terms in the heat budget are the surface fluxes of water vapor and sensible heat, the horizontal temperature advection, and the vertical fluxes of heat through the thermocline due to intermittent microscale turbulence. The surface fluxes will be estimated on the basis of the bulk aerodynamic formulae based on surface data derived from drifting buoys that carry meteorological instrumentation, ships of opportunity, and remote satellite sensing. Moored arrays of current meters, vertical profilers, and drifters drogued to various depths are the principal existing tools available for monitoring the horizontal temperature advection. The vertical flux of heat through the thermocline will be inferred from *in situ* measurements of the rate of turbulent dissipation of mechanical energy and the microstructure of the temperature field. In addition, the local heat storage in the mixed layer will be estimated on the basis of data derived from moored or drifting thermistor chains and XBTs from ships of opportunity.

Apart from the turbulence measurements, which can be made only from oceanographic vessels, the program will rely heavily on oceanographic and meteorological data from unattended instruments on moored and drifting buoys, interrogated by satellites. Inexpensive, calibrated, remotely located drifting buoys that follow the upper ocean water motion at various levels play an especially important role. And it should be emphasized that satellite data are needed in order to provide a regional scale context for interpreting the isolated measurements of sea-air fluxes from the various instrumented platforms. Improved techniques are needed for inferring the net radiation budget at the air-sea interface and the low-level humidity field on the basis of satellite-based measurements. A schematic summary of the observing platforms required for the central Pacific program is shown in Figure 7. It is estimated that this experiment would run for a five-year period beginning October 1983.

Western Pacific Program. Although the interannual variability of SST is smaller in the western Pacific than in the central and eastern Pacific, a number of recent modeling studies indicate that the atmospheric circulation might nevertheless be extremely sensitive to SST variability in that region. From an oceanographic

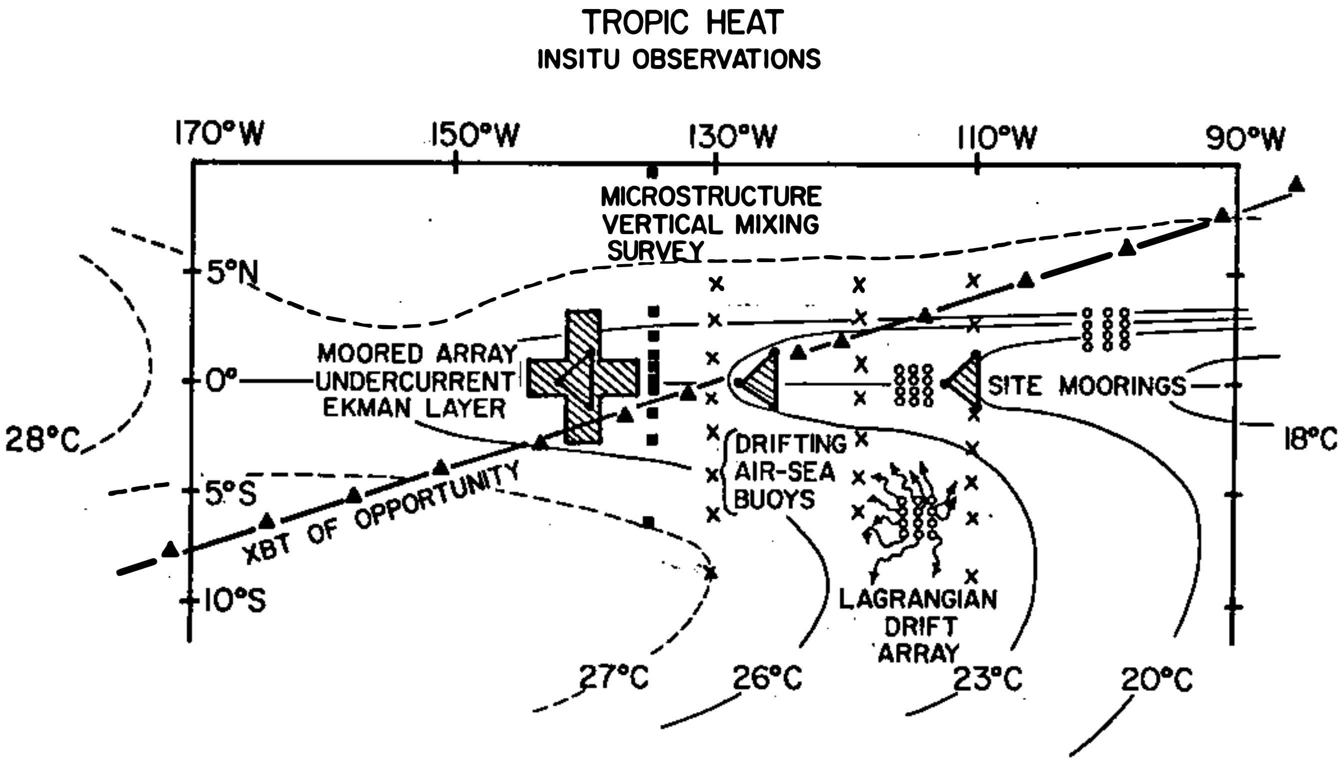

FIGURE 7. Schematic depiction of the observational program elements proposed for the NSF-sponsored Tropic Heat Program. It is assumed that satellite observations will also be available. The surface temperature is drawn for a typical June-September period when a "cold tongue" is well developed along the equator and when there is a large east-west temperature gradient south of the equator.

standpoint the western Pacific is characterized by dramatic and widespread changes in sea-level and thermocline depth that occur in association with the EN phenomenon further to the east. Furthermore, there is considerable theoretical and modeling evidence that suggests that in at least some cases, EN events may be viewed as a remote response to sudden changes in wind stress over the equatorial western Pacific. A detailed program plan does not yet exist for a process experiment in the western Pacific, although some oceanographic monitoring is being carried out as part of the western Pacific (WESTPAC) program. In view of the meteorological and oceanographic importance of this region, it is worth considering whether a focused regional observing and data collection program might be needed. It is suggested that a special international symposium on the western Pacific be held to (1) assess current knowledge of the region and (2) to identify interested scientists who might form the nucleus of a new program. The WESTPAC group might be a logical focal point for organizing these activities.

2.2 OBSERVATIONS: A METEOROLOGICAL PERSPECTIVE

The observations required for the meteorological objectives of ENSO are somewhat more global in scope than those described in the previous section, but there is considerable overlap between the two sets of requirements.

2.2.1 Atmospheric Monitoring and the World Weather Watch

The meteorological counterpart of the monitoring effort is based on the World Weather Watch (WWW) network, which exists primarily for the support of operational weather forecasting. For the purposes of ENSO, requirements for spatial coverage over the northern hemisphere extratropics are not as stringent as for weather forecasting, but year-to-year time continuity of certain components of the observational system, such as meteorological satellites and isolated island stations, is more critical, and a greater density of observations in certain key regions is needed.

It is assumed that the WWW will not only be maintained at its current level, but will in fact be improved during the lifetime of the ENSO program. In its present configuration, the network is adequate for many aspects of the program, but a modest enhancement of observations from the equatorial Pacific is critical in addressing the key issues related to the ENSO phenomenon.

2.2.2 Augmentation of the Ground-Based World Weather Watch Network

The requirement for monitoring the atmospheric circulation in the neighborhood of the equator can partially be met by establishing or continuing to maintain routine surface and upper air observation stations on a small number of islands located near the equator at strategic longitudes. These include the Galapagos, Christmas, Canton, Nauru, and Tawara Islands. Automatic surface observing stations are needed on a few other near-equatorial islands, such as Clipperton and selected members of the Line Islands, e.g., Malden. In addition to the routine meteorological information collected, the oceanographic research vessels participating in ENSO should make regular atmospheric soundings, on a non-interference basis, and efforts should be made to upgrade the collection and quality control of marine surface observations from ships of opportunity in the tropical Pacific.

In order to supplement the surface observational network, particularly in the huge areas between ship tracks (see Figure 5), it will be necessary to maintain a number of meteorological buoys during the lifetime of the program. These systems will, of course, complement the large-scale ocean monitoring program described in 2.1.1. Of highest priority are limited arrays of buoys deployed in three strategic areas:

- the southeast tropical Pacific, in the region of almost nonexistent surface observations (as an alternative to moored buoys, an automatic station on Peter and Paul Island might be considered);
- the near-equatorial latitude band, across the entire breadth of the Pacific; and
- in the poorly sampled region of the Intertropical Convergence Zone (ITCZ).

All buoys should be instrumented to provide measurements of sea surface and air temperature or temperature difference and humidity sensors, if practicable. Buoys in the equatorial belt should also be equipped to measure wind speed and direction, while wind speed and pressure measurements are adequate at higher latitudes. The buoy network in the southeast tropical Pacific must be adequate for resolving the major variations in the southeast trade winds and the large-scale variations in the southeast Pacific high, while the combined meteorological/ oceanographic buoy network in the equatorial belt must resolve the wind fluctuations of importance to the large scale ocean dynamics. The network in the vicinity of the ITCZ must resolve the variations in low level winds associated with changes in position and intensity of the convergence zone.

In addition, a fairly sparse network of drifting buoys is needed over the southern hemisphere ocean, including the remainder of the South Pacific Ocean as well as the Indian Ocean, and the South Atlantic Ocean and the Antarctic Circumpolar Current. Since fluctuations on the ENSO time-scale have much larger characteristic horizontal scales than those on daily weather maps, the network need not be as dense as the one that was in place during the First GARP Global Experiment (FGGE). Since the planning and implementation of buoy programs require long lead times, it will be important to define observational requirements clearly at an early stage.

2.2.3 Need for Continuous Satellite Coverage

A vital part of the WWW, as it stands, is the remote sensing of the atmosphere from space. Measurements from satellites are the only feasible approach for obtaining the truly global perspective required for monitoring the atmospheric part of the SO. Included at present are at least two U.S. geostationary satellites and one or two polar orbiting sun-synchronous satellites. These systems provide visible and infrared imagery, infrared and microwave soundings that can be used to infer the vertical distribution of atmospheric temperature and moisture, and cloud motion vectors that provide information on the wind field. The polar orbiters are also used to interrogate remote surface stations, such as drifting buoys.

Continual coverage by geostationary satellites over the Pacific Ocean, the Americas, and elsewhere in the tropical belt is essential to ENSO. At least one polar orbiter is required at all times, and that can best be guaranteed by the continual presence of two polar orbiters. Any breakdown in satellite coverage would place the entire ENSO program in jeopardy. Continuity in coverage is essential.

2.2.4 Special Observation Needs

- A knowledge of surface wind is essential for determining the exchanges of momentum between the atmosphere and oceans that drive the ocean circulation, and for parameterization of air/sea exchange of heat and water vapor by the bulk aerodynamic method. This information can most readily be obtained by satellite-borne scatterometers.
- Cloud Motion Vectors provide a large amount of potentially useful proxy low-level wind data over the large trade wind regions, although they are of more limited usefulness in zones at deep convection, i.e., the ITCZ and the South Pacific Convergence Zone (SPCZ). Determination of these vector fields requires processing and assembly of information from the Indian and Japanese as well as the U.S. geosynchronous satellites. The relationship between cloud level winds and surface winds may be a complex function of time and space, particularly near the equator.
- A knowledge of the sea surface temperature distribution is essential for specifying the lower boundary condition in many atmospheric models. It is one of the indicators of oceanic heat storage, and it is required for the calculation of air-sea fluxes of moisture, sensible heat and radiation. Needed are improved global sea-surface temperature analyses, derived from a more sophisticated blending of satellite information and surface ship observations.
- Routine quantitative estimates of precipitation, or an index of precipitation, averaged over areas on the order of 2°x2° are needed for the entire Pacific-Indian Ocean tropical region. A product of this type does not yet exist, but recent studies relating radar returns and satellite radiance data from the GARP Atlantic Tropical Experiment (GATE) A/B array, together with the apparently successful use of infrared (IR) data for describing large-scale variations of precipitation in the tropical Pacific indicate that it might be feasible to develop one. Maps of total precipitable water would also be of considerable value; such maps could be generated on the basis of satellite-observed IR radiance data.

- For development of improved methods of estimating precipitation it would be highly desirable to have condensed archives of visible and infrared satellite imagery, including histograms of the frequency distribution of radiances. Because of the high volumes involved, full resolution images are virtually inaccessible to researchers interested in phenomena with monthly time-scales or longer.
- Detailed knowledge of the properties and extent of clouds is needed so as to be able to infer the radiative flux divergence for atmospheric columns. Some overlap exists between the requirements for ENSO and those for the International Satellite Cloud Climatology Project (ISCCP), which has been proposed for a five-year period during the 1980's.
- The surface energy fluxes between the atmosphere and ocean are of vital importance for both the ocean and the atmosphere individually, and especially for the coupled problem. Algorithms determining surface radiative fluxes, based mainly on satellite data, are under development and appear promising. Surface fluxes of sensible and latent heat may be computed using bulk aerodynamic formulae, which require a knowledge of the surface wind, air-sea temperature differences, sea-surface temperature, and surface atmospheric humidity. While there are a number of uncertainties and difficulties in obtaining these quantities with the desired accuracy at any instant, the situation is much more promising on the monthly time scale, which is adequate for most purposes. Further development of techniques for obtaining these quantities or proxy variables by remote sensing and from the augmented WWW should be encouraged.

2.3 HISTORICAL DATA SETS

Many of the recent advances in understanding of the ENSO phenomenon are direct or indirect results of analyses of historical data sets. Further analysis of these data sets is necessary in order to provide a proper context in which to interpret the new observations described in the previous sections. These analyses will also serve as a basis for initializing, forcing, and verifying numerical models, for testing forecasting schemes, and for monitoring and testing new hypotheses concerning physical mechanisms. Hence it is appropriate to recognize this analysis activity as an integral part of the ENSO program plan and to recommend that a substantial fraction of the funding available to the program be devoted to broadening the scope and improving the quality of certain key historical data sets available to researchers working in this field. Specific recommendations relating to the management of historical data sets are presented in 3.1.

2.4 MODELING

The goal of the modeling effect is to understand the dynamics of the ENSO phenomenon throughout a complete cycle. This goal will require the development of coupled ocean-atmosphere models that are global in extent and that can be integrated for long periods of time (at least 15-20 years). These models will range from dynamically simple ones that illustrate specific interaction mechanisms to ocean and atmosphere general circulation models that are capable of realistically simulating the phenomenon. In addition, atmospheric models with prescribed SST distributions, as well as oceanic models with prescribed wind stress and heat flux distributions, will be useful. Finally, regional models that can focus on a particular aspect of the circulation (e.g. the tropical Pacific) are needed. While much modeling research is already under way, it can be expected that the availability of new data of improved quality and coverage will stimulate additional activity.

2.4.1 Atmospheric Models (Prescribed Ocean)

Present general circulation models are capable of simulating many observed features of the atmosphere's general circulation, both in the tropical and higher latitudes. These models simulate well not only the mean circulation but also transient features such as teleconnections and blocking. Simulations of the atmosphere's response to an imposed equatorial Pacific sea-surface temperature anomaly have been carried out over the past decade with considerable success.

Future anomaly experiments should be of sufficient length to allow statistically significant results to be obtained for most of the major features both within and outside the tropics. Because of the non-linear nature of the response, the SST anomalies should be of a realistic magnitude. Experiments for a fixed time of year are probably the most economic in computer time, but the results should be confirmed by experiments including the seasonal variation.

The quality of the best simulations of the atmospheric circulation is generally very good. The simulation of the rainfall distribution is of particular importance in the tropics; a good control simulation is essential if predictions of economically important changes in tropical rainfall are to be taken seriously. The rainfall is sensitive to the simulation of region of ascent and to the parameterization of boundary layer and convective processes and droplet condensation and evaporation. These therefore all deserve special attention in the development of atmospheric models.

There is relatively little published material on the quality of simulation of aspects of the atmospheric models relevant to ocean-atmosphere interaction. The ocean mixed layer is particularly sensitive to the surface wind because the mixing energy is highly dependent on the wind speed. This and the realistic simulation of the stress curl, which is of great importance in determining the ocean circulation, are likely to be particularly difficult problems in coupled models. There may be a need for higher north-south resolution in the atmospheric models in order to obtain sufficiently accurate representation of the surface stress curl in the vicinity of the intertropical convergence zone.

There are large changes in the modeled latent heat flux due to SST anomalies in the eastern and central tropical Pacific but the changes vary considerably between experiments, partly because of the different SST anomaly patterns. Changes in sensible heat fluxes can also be important because upwind of the anomalies in the east Pacific, boundary layer air is crossing the SST gradient in a region where net condensation is small, so that heating of the air mainly occurs through sensible heat fluxes.

An area of much present concern in both atmospheric and coupled models is the representation of clouds. In the tropics, cloud is a major factor in variations of the net radiation of the ocean surface and so, in a coupled model, is important for the ocean thermodynamics. The cloud amounts, heights, and optical characteristics are all important and all difficult to parameterize.

2.4.2 Ocean Models (Atmosphere Prescribed)

In the last decade a wide variety of ocean models have been used successfully to understand the response of the tropical ocean to both steady and time-varying distributions of surface wind stress. They range from simple, linear, reduced-gravity models to sophisticated, oceanic general circulation models, and simulate many observed features of the circulation surprisingly well. Of particular importance to the present program is the existence of several models of EN. These models all indicate that changes in the remote winds are connected to EN events at the South American coast via the equatorial wave guide. Recently, a linear reduced gravity model driven by eighteen years of realistic winds has been used to simulate observed sea level variations in the tropical Pacific (Figure 8). Model EN events are caused by a relaxation (or reversing) of the trades in the far western Pacific.

An important need for this program is the development of models that produce realistic SST anomalies. This need requires the inclusion of proper thermodynamics in the tropical mixed layer. (Models in which thermocline displacements are interpreted as SST changes are not adequate. In some parts of the tropical Pacific large thermocline displacements are not accompanied by corresponding changes in SST, e.g., western Pacific). The relationship between baroclinic equatorial disturbances, thermocline displacements, upwelling, horizontal advection, heat flux, and sea surface temperature must be understood and modeled. Moreover, the model results we do have are extremely sensitive to strength and distribution of the vertical mixing processes for heat and momentum. (Models without strong mixing near the surface may develop unrealistically large surface currents, and the degree of eddy development and other non-linear effects are sensitive functions of the size of mixing parameters). Thus, mixing processes must be properly parameterized in the upper layer thermodynamic models.

Because of the necessity to include mixed-layer processes and other thermal physics in the models, they will be more complex than those used in past studies of equatorial dynamics. Accurate modeling of the heat budget and the circulation in the eastern Pacific will probably require fully non-linear, stratified, multi-level

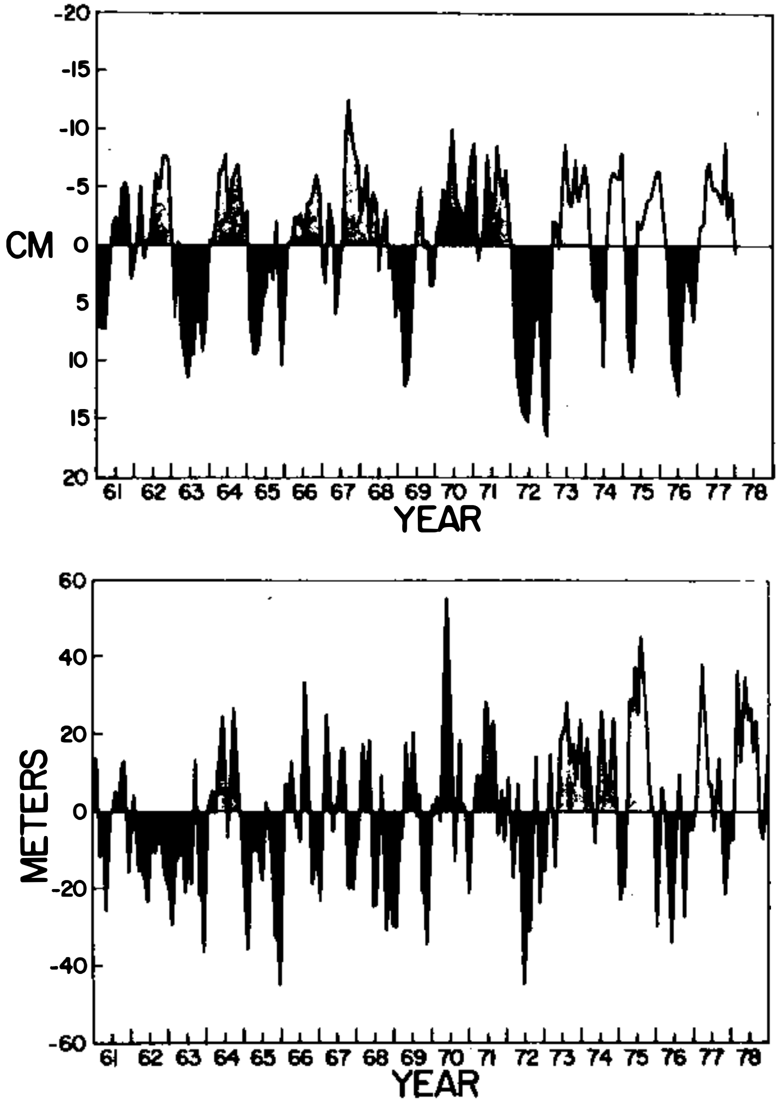

FIGURE 8. Top: Time series of observed sea level at the Galapagos Islands from 1961-1977, inclusive. Data for 1978 are not available. Periods when the mean monthly sea level is higher than the long-term annual mean are shaded black. Bottom: Model pycnocline height anomaly (PHA) at the Galapagos Islands. Periods when the pycnocline is deeper than the 18-year mean are shaded black (Busalacci et al., 1983).

numerical models. Simpler process models, though incapable of truly realistic simulations, will be an important aid in increasing our understanding of the relevant physics as well as the interpretation of GCM results.

The major component of the circulation of the upper equatorial oceans is wind-driven. Modeling this circulation requires a very good knowledge of the surface wind field in order to make reasonable estimates of the wind stress curl. (The precise accuracy and resolution needed depends on the problem of interest; for example, detailed modeling of the seasonal response calls for ten-day mean winds with a spatial resolution of a few degrees in longitude and a degree or less in latitude). The wind field over the tropical Pacific exhibits a very complex structure, making it difficult to form reliable estimates of wind curl from a limited number of measurements. Moreover, since the equatorial band cannot be separated from the tropical circulation as a whole, models will require the wind field over (at least) the entire tropical Pacific. EPOCS and the Pacific Equatorial Ocean Dynamics (PEQUOD) programs are currently addressing this problem.

Although a precise knowledge of the surface heat flux may not be required for modeling the equatorial momentum budget, the surface heating must be known in order to develop ocean models that generate SST anomalies. So, a good knowledge of the distribution of surface heating to the overall heat balance is crucial. The measurement of this balance is an important part of the Tropic Heat program.

Vertical turbulent processes are too small scale and too rapid to be simulated. So, observations that lead to a parameterization of vertical mixing in terms of large-scale flow features (such as the vertical shear of the currents, stratification, etc.) will be of great value to modelers. Measurements of turbulence near the surface, in the thermostad, and in the vicinity of the undercurrent are especially desirable. Such a measurement program is also part of tropic heat.

2.4.3 Coupled Ocean-Atmosphere Models

As noted earlier, models of the coupled ocean-atmosphere system have a central role to play in the study of the ENSO phenomenon. Such models can be used to guide the development of observing and monitoring systems, can guide the interpretation and diagnosis of data sets (both observational and simulated), can provide evidence of the sensitivity of the phenomena to specific processes through numerical experiments under controlled conditions, and can exploit the possibilities of prediction in a systematic manner.

Just as there are a wide variety of atmospheric models for different purposes, it is anticipated that a hierarchy of coupled models will be useful for exploring the range of space and time scales involved in ENSO. These range from simplified models of the upper ocean coupled with a highly simplified representation of the atmosphere, to fully coupled comprehensive general circulation models. In carefully designed experiments, these models can be used to determine which physical processes are essential to the ENSO, and with what resolution they have to be portrayed. Of particular importance to the driving of the oceanic part of the coupled model are the patterns of the surface wind and surface heat flux simulated by the atmospheric part; the successful parameterization of these fluxes in the tropics may be the most critical aspect of a coupled model's usefulness for ENSO research.

From the applications of simplified coupled models that have already been made to portions of the ENSO phenomenon, it is clear that the degree of detail and sophistication required to successfully portray the behavior of the tropical ocean in response to atmospheric forcing needs to be explored. By progressively adding new features to such models, and by carrying out a systematic program of numerical experimentation, coupled ocean-atmosphere models can provide valuable insight into the mechanics of ENSO, while interacting with the ongoing observational program. The ENSO provides a strong motivation for the development and application of coupled models, and this opportunity should be vigorously pursued. Such models, after all, are the form in which we will ultimately seek to express our understanding of ENSO; it is therefore important that experience in the design and application of coupled models be initiated as soon as possible and be carried on throughout the program.

3

DATA MANAGEMENT

There are three types of data that must be accommodated in the ENSO program. The first is historical data already archived in various locations. These data will be processed and utilized in continuing research as described in section 3.1. The second type of data consists of that of a continuing nature created by, e.g., the National Meteorological Center (NMC) and the Climate Analysis Center (CAC) of the National Oceanic and Atmospheric Administration (NOAA). These data sets consist of the conventional World Weather Watch (WWW) data, the analyzed (meteorological) maps, and oceanographic data required for the El Nino (EN) watch. These data will be termed the operational monitoring data and are described in section 3.2.

The final type consists of the data collected by the field phase portions of the ENSO experiment components. These data require a data management plan: the appropriate considerations are given in the final section 3.3.

3.1 HISTORICAL DATA SETS

The recent advances in the description and understanding of the ENSO phenomenon have been made possible largely by the assembly of a small number of key data sets. These include: (1) the historical ship-of-opportunity surface marine observations, mostly since 1950, but with some observations as early as the mid-nineteenth century, (2) the Pacific island rainfall data, primarily during the past 50 years, (3) routine surface observations, primarily during this century, (4) upper-air observations and operational grid-point analyses, primarily since the 1950s, and (5) gridded global satellite visible and infrared radiation data available since 1973 and nephanalysis for the period 1965-1974.

Atmospheric data must address two basic scales of interest, the global scale, which reflects the scale of the Southern Oscillation (SO) itself, and the regional scale, for phenomena over the tropical Pacific. Vigorous and coordinated efforts to locate, acquire, and assemble key historical data must receive a high priority in the program. A number of tasks can be singled out as being of highest priority.

3.1.1 Upgrading of the Global Surface Marine Data Base

The emphasis on the large-scale sea-air interaction processes of the SO dictates a central role for the historical ship-of-opportunity surface observations. There continues to be a huge amount of surface marine data in manuscript form at various locations throughout the world. Although the cost of keypunching all these data is prohibitive, there are undoubtedly subsets that should be assigned a high priority for conversion to machine-readable form. The first step in this process is to assign priorities to the various data sets that might be keypunched. The possibility of an international effort under the World Climate Program representing a continuation of the Historical Sea-Surface Temperature Data Project (HSSTDP) should be examined.

High priority should be attached to the upgrading, merging, and consolidation of the existing NMC marine decks through the international exchange of machine-readable data, the application of quality control procedures, and the introduction of more efficient formatting. For some elements in the marine surface data, the elimination of duplicate observations is also a high priority task.

Ship-of-opportunity observations in the marine decks are randomly located in the space/time domain. Some type of space/time summarization is required if these data are to be used effectively. Two types of basic summarization are desirable.

- A basic summarization of mean monthly statistics should be made on a 2°x2° grid. These gridded data should include not only means but also variances and covariances necessary to estimate fluxes from bulk aerodynamic relationships. Key parameters include surface wind and wind stress, sea-level pressure, sea-surface temperature (SST), and salinity.

- A separate summarization of monthly data should be made for heavily traveled shipping lanes. There will be times and areas for which the 2°x2° data are inadequate for constructing reliable time series. Conversely, there are relatively heavily traveled shipping lanes for which the data are uniformly dense in time. Reliable conclusions can sometimes be drawn more easily from detailed analyses of these ship track data than from the less homogeneous 2°x2° full field analyses. The contents of the marine deck should be inventoried on a fine spatial resolution (1°x1°) to identify the times and locations of regions or lanes of dense observations. Data from these selected regions should then be summarized as an important subset to the basic 2°x2° data set. The Pacific and Indian Oceans should be given highest priority for both these data sets.

In these and other similar efforts, it is important to avoid duplication of effort. A small advisory committee of experts should be established to evaluate the current status of the surface marine data base and prepare a coordinated plan of action and review progress.

3.1.2 Assembly of Surface Meteorological Time Series

Observations of rainfall, pressure, and other atmospheric parameters measured at tropical stations should be consolidated into an SO data set. Emphasis should be placed on obtaining all available observations at Pacific island stations and locating long, newly continuous records at selected stations around the globe. Such time series should serve as useful indices of the interannual and interdecadal fluctuations of the SO. Data in manuscript form now residing in various national meteorological data centers should be inventoried for possible selective conversion to machine-readable form. A program for routine updating of this data set should also be established.

3.1.3 Assembly of Oceanographic Data Sets

Observations of sub-surface temperature and salinity are needed for studies of interannual variability of the tropical Pacific. The frequency and regularity of these data are not sufficient for constructing time-series, but there are sufficient numbers of observations available for studying year-to-year changes and constructing composites. Data in the various oceanographic repositories need to be compiled and reformatted for each availability. A great deal of useful data resides at institutions in other countries. These need to be catalogued and made available where possible. This activity will require a national focal point, the planning for which should be accomplished in a centralized data management function (see section 3.3).

3.1.4 Assembly of Global Meteorological Analysis Products

Operational analyses of meteorological variables developed by the U.S. NMC, U.S. Fleet Numerical Oceanographic Center, and equivalent agencies in other nations have provided in recent years the best available spatial coverage of the SO. Archiving of key operational products, such as tropospheric wind and height, should be continued. Global analyses have been produced operationally on a routine basis only during the 1980s. However, it should be possible to construct global data sets of height, temperature, and wind for much of the 1970s by consolidating the Northern Hemisphere, Southern Hemisphere and tropical analyses for each synoptic time into a single global analysis. Global analyses of sea-level pressure, 850 and 200 mb wind fields, and 500 mb height deserve highest priority.

3.1.5 Recovery of Cloud Motion Vectors for the Pre-First GARP Global Experiment (FGGE) Period

There exist archives of infrared satellite imagery on digital tape that would be suitable for computing cloud motion vector (CMV) fields for the period subsequent to summer 1974. In the FGGE and post-FGGE period these data have had considerable impact on the operational global meteorological analyses. However, during the period 1974-1978 the information inherent in the cloud motions was used in the analyses only to a very limited extent, and therefore it constitutes a potentially valuable source of historical data that has not yet been exploited. Recovery of complete CMV fields for this entire period would be costly, and the utility of such data has yet to be demonstrated. Therefore, it might be useful to undertake a pilot project for a limited time period or periods focused on the 1976 EN event, with emphasis on trade wind-level fields in the tropical Pacific.

3.1.6 Coordination With Existing Efforts

It should be emphasized that efforts toward achieving the objectives outlined in this section are already under way at a number of institutions (e.g., the HSSTDP) organized through the office of NOAA's Environmental Research Laboratories, the National Center for Atmospheric Research (NCAR) Data Library, and the Master Oceanographic Observation Data Set (MOODS) Project at the U.S. Navy Fleet Numerical Oceanographic Center. The ENSO program promotes the continuation, expansion, and coordination of these efforts and complementary efforts at other institutions throughout the world.

3.2 OPERATIONAL MONITORING DATA

The CAC of NOAA presently collects and examines various types of meteorological data in the form of bi-monthly average statistics. This material is used principally in the EN watch portion of the ENSO program. The average statistics include global meteorological analyses and sea-surface temperature analyses produced by the NMC; processed radiometry data produced by the National Environmental Satellite Service (NESS); and derived tropical precipitation and momentum and energy flux estimates.

It is anticipated that the CAC will continue to collect this material. An archiving and formatting scheme has been worked out. The twice-daily meteorological data received over the Global Telecommunications System of the WWW as well as the global analyses produced at NMC are routinely archived at the National Climatic Center (NCC) and NCAR. In summary, no special data management considerations are needed for the data in this category.

3.3 MANAGEMENT OF FIELD PHASE DATA SETS

The observing sub-systems recommended for ENSO are capable of producing a vast amount of diverse data. There are fundamental differences in observing techniques from different platforms in space, on the ocean, and on island stations. Nevertheless, the whole data flow must be considered within a unified framework since the output of the experiment should result in a data set as complete and internally consistent as possible, readily accessible to all of the participants and to the interested scientific community. Hence, a data management and processing plan must be an integral part of the experiment.

3.3.1 Centralized Data Management Function

A data management and program office should be identified whose responsibilities include:

- Development of schedules for the processing of the data sets for the EN watch;
- Development of documentation formats for the data collected by the experiment;
- Identification of specialized processing data centers as required.

3.3.2 Data Definitions Modeled After the Global Weather Experiment

- Level I raw data. Those general instrument readings that require conversion into meteorological and oceanographic variables specified in the data requirements. The raw data records are to be retained by the participants and are not anticipated to be part of the general data flow.
- Level II--meteorological and oceanographic variables obtained from many kinds of simple instruments <u>or</u> derived data from Level I data, i.e, average wind, sea level, SST, etc. These are divided into two categories.
- Level IIa data set--WWW data and those required for a quick look and EN monitoring. These should have a negotiated but firm cutoff time.
- Level IIb data set--The ENSO research data set that is distinguished from the IIa by a delayed cutoff in order to acquire a complete data set.

- Level III data set--ENSO state parameters. An internally consistent data set in grid point form obtained from Level II data by an objective analysis technique.

3.3.3 Variable Measurement

Table 1 attempts to list the meteorological and oceanographic variables required for ENSO together with the means to acquire the measurements of that variable.

The matrix shown is intended to be a summary of what is planned in the measurement and/or field phase content of the program plan. It does not include those variables that are measured as part of the operational meteorological and oceanographic observing systems, principally the WWW. Thus, such important quantities as atmospheric temperature and moisture, which are routinely measured by the operational satellites, do not appear explicitly.

Each entry in the matrix can be identified with an existing or proposed activity or participant in the ENSO program. The heterogeneous nature of the data and their point of origin is illustrated by the matrix.

Future planning and consideration may indicate that vacant entries in the matrix can be filled in.

TABLE 1 The Meteorological and Oceanographic Variables Required by the ENSO Program

Variable	Satellites	Research Ships	Ships of Opportunity	Buoys	Remote Stations
Sea level	Altimetry	Hydrography	XSTD[a]		Tide gauges
Ocean heat content		XBT	XBT	Thermistor chains	
Ocean currents				Current meters	
Moisture flux	(surface insolation)	Bulk method		Bulk method	
Wind stress	Scatterometer (cloud drift winds)	Wind	Wind	Wind	Wind
Sea-surface temperature	Radiometry	XBT	Thermometry	Thermometry	Thermometry
Sea level pressure			Barometry	Barometry	
Liquid water content, column total water vapor, and precipitation rate	Multi-spectral microwave radiometry				
Upper atmospheric flow	Cloud drift winds	Soundings			

[a]XSTD = Expandable salinity, temperature, depth.

4

COORDINATION WITH OTHER PROGRAMS

4.1 NATIONAL PROGRAMS

ENSO is visualized as a U.S. component of the recently defined international program for study of the interannual variability of the Tropical Ocean and the Global Atmosphere (TOGA), a component of the World Climate Research Program (WCRP). ENSO, as defined in this report, is focused on oceanic processes in the tropical Pacific and on atmospheric processes globally. TOGA is yet to be planned in detail. It will, however, have components that go beyond those of this ENSO plan, involving tropical ocean studies in the Atlantic and Indian Oceans. As ENSO evolves, it must be closely tied to the other components of TOGA.

ENSO can profit from cooperation with other experiments in the WCRP. Many of these programs [e.g., the World Ocean Circulation Experiment (WOCE), Cage, International Satellite Cloud Climatology Project (ISCCP)] will have need for common facilities that can be of benefit as well to ENSO and TOGA. Examples are for satellites, ocean and atmosphere monitoring systems, modeling facilities, and observational technique development. Plans for the other WCRP experiments are still being developed, so that it is premature to spell out the details of cooperation with them.

The Monsoon Climate Program (MCP) is directed at an understanding of the nature of long-period fluctuations of monsoons, the mechanisms that determine the interannual variability of monsoons, the predictability of the variations, and the relation of the long-period fluctuations to planetary-scale circulations. The close relation between Indian and Pacific Ocean phenomena within the SO argues for close cooperation between ENSO and the MCP as related parts of the WCRP.

Two regional programs in the Pacific are worth special attention in developing cooperative plans for ENSO. These are the western Pacific (WESTPAC) program in the western Pacific and the Estudio Regionale del Fenomino El Nino (ERFEN) program in the eastern Pacific.

WESTPAC is an international scientific program involving the countries on the western rim of the Pacific (and the United States). One of the programs being sponsored by WESTPAC is the improvement of the data coverage on heat content currents and sea level in a large area of the western Pacific. This involves the encouragement of member countries to contribute observing platforms and sensors. A number of countries have already established networks and more are planned. The Japanese Hydrographic Office has been designated as the repository for the data. This data base is of great potential value to the ENSO studies of the ocean. Exchange of data between ENSO and WESTPAC will be of great benefit.

Four countries on the west coast of South America began in 1974 to cooperate in the international program, ERFEN. Under the auspices of the Commission Permanente del Pacifico Sur (CPPS), the Intergovernmental Oceanographic Commission (IOC), and the World Meteorological Office (WMO), this program provides a mechanism for coordination of marine research activities, upgrading of operations in support of meteorological services, sharing of data, and identifying training and technical needs. The long-range objectives of ERFEN reflect exactly the regional manifestation of ENSO. Close cooperation with scientific agencies in Peru and Ecuador have already been initiated within the EPOCS program, and will be increased for mutual benefit.

4.2 INTERNATIONAL PROGRAMS

The phenomena to which ENSO is addressed are inherently global. The SO has world-wide oceanic and atmospheric manifestations. Tropical sea-surface temperature anomalies correlate with variations in the intensity of Indian monsoon rainfall, with droughts in India and China, and with cold winters in North America. The study of such global phenomena must be done internationally.

The United States needs the participation of other countries in the study of the SO. This participation should occur at many levels and for many components of the research work. The program elements on which ENSO is based are already international.

Just as the benefits of programs in prediction of the ENSO phenomena will accrue to individuals of all nations, so do the logistics and economics of systematic large-scale monitoring of the ocean and the atmosphere mandate that it must be undertaken as an international enterprise. Several nations have already initiated or participate in activities that contribute strongly to the ENSO program. Among these may be noted the activities of the WWW and the Integrated Global Ocean Station System (IGOSS), which provide regular sampling of the global atmosphere and some oceanographic data. Oceanographic monitoring activities are generally less well institutionalized. The principal oceanographic monitoring activities are done by means of the international sea-level network, and programs primarily of the United States and France for regular collection of data from ships of opportunity, using merchant vessels of many countries.

Modeling and theoretical studies carried out in other countries have played an important role in providing a scientific basis for ENSO. Continued international cooperation will be needed in modeling for optimum progress. As an example of the type of activity that should be strongly supported by ENSO, there are the cooperative SST sensitivity experiments being carried out with atmospheric general circulation models. This activity is sponsored by the Working Group for Numerical Experimentation of the WCRP. The SST sensitivity experiments are intended to pinpoint those areas in the ocean where SST anomalies have the greatest effect on the large-scale atmospheric flow. At present six nations are participating in this international undertaking, committing a formidable array of modeling experience and computer resources to this cooperative activity.

Several special sampling and research programs that will be of particular value to ENSO have already been initiated by other countries. An outstanding data set along 137°E in the western Pacific exists as a result of a monitoring program initiated by Japan in 1967. In the southwestern Pacific, similar monitoring was carried out by France between 1965 and 1973 along 170°E and will be reactivated in 1984. On the eastern side of the basin, Peru, in view of the great value of the coastal fisheries and the economic impact of varying environmental conditions, of which the major manifestation is EN, has endeavored to sustain a research program on the EN. Likewise, Equador is planning quarterly cruises in the region between South America and the Galapagos Islands in support of research on EN.

Basic measurements, such as sea-level and temperature data, will continue to be of great value in the ENSO research program, and can be collected by many nations, including developing countries. For example, much of the quantitative historical information on the ENSO phenomena derives from many years of collecting data at coastal stations by Peruvian scientists. Implementation of these observations will usually require some technical assistance and training, and can be used to help realize scientific aspirations in these countries. As these aspirations develop, it will become possible to have the programs evolve from simple surface sampling to more general oceanographic observations using regional vessels of opportunity. For example, sea-level data from the Indonesian archipelago would be of great value to ENSO in relating Indian Ocean and western Pacific phenomena. Because oceanographic programs are less well institutionalized than meteorological programs in most of these countries, mechanisms must be developed to facilitate their commitment to the international effort.

U. S. participation in the WCRP should be coordinated through the Joint Scientific Committee (JSC) for the WCRP and the Committee on Climatic Changes and the Ocean (CCCO). The JSC/CCCO are developing the international plans for studies of the interannual variability of the TOGA. ENSO, as a principal U.S. contribution to TOGA, will likely influence its planning.

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GLOSSARY

AXBT	Airborne Expendable Bathythermograph
BASC	Board on Atmospheric Sciences and Climate
CAC	Climate Analysis Center
Cage	Large scale heat budget experiment for the North Atlantic Ocean region
CCCO	Committee on Climatic Change and the Ocean
CMV	Cloud Motion Vector
CPPS	Commission Permanente del Pacifico Sur
CRC	Climate Research Committee
EN	El Nino
ENSO	El Nino/Southern Oscillation
EPOCS	Equatorial Pacific Ocean Climate Studies
ERFEN	Estudio Regionale del Fenomino El Nino
ERL	Environmental Research Laboratories
FGGE	First GARP Global Experiment
GARP	Global Atmospheric Research Program
GATE	GARP Atlantic Tropical Experiment
GCM	General Circulation Model
HSSTDP	Historical Sea-Surface Temperature Data Project
IGOSS	Integrated Global Ocean Station System
IOC	Intergovernmental Oceanographic Commission
IR	Infrared
ISCCP	International Satellite Cloud Climatology Project
ITCZ	Intertropical Convergence Zone
JSC	Joint Scientific Committee
MCP	Monsoon Climate Program
MOODS	Master Oceanographic Observation Data Set
NCAR	National Center for Atmospheric Research
NCC	National Climatic Center
NESS	National Environmental Satellite Service
NMC	National Meteorological Center
NOAA	National Oceanic and Atmospheric Administration

NRC	National Research Council
NSF	National Science Foundation
PEQUOD	Pacific Equatorial Ocean Dynamics
PHA	Pycnocline Height Anomaly
POMS	Pilot Ocean Monitoring Studies
QBO	Quasi-Biennial Oscillation
SO	Southern Oscillation
SPCZ	South Pacific Convergence Zone
SST	Sea Surface Temperature
TOGA	Tropical Ocean and the Global Atmosphere
WCRP	World Climate Research Program
WESTPAC	Western Pacific
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment
WWW	World Weather Watch
XBT	Expendable Bathythermograph
XSTD	Expendable salinity, temperature, depth

APPENDIX A

THE 1982-1983 PACIFIC EPISODE

As this scientific plan was being developed, a major warming event unfolded in the Pacific, with associated weather anomalies on a global scale. This phenomenon, by most measures the most intense such event on record, was atypical in many respects. The description below serves both to provide a realistic context for the plans presented in this report and to remind us that nature holds many surprises in reserve.

Conditions over the equatorial Pacific during early 1982 were not recognized, at the time, as precursors of an impending warm episode. There had been no "buildup phase" with abnormally strong trade winds, which has often preceded such events in the past. Sea surface temperatures along the South American coast were near normal, and the surface anticyclone over the southeast Pacific was near normal strength. By June, however, there were indications of important and unusual changes taking place in both the ocean and atmosphere of the tropical Pacific. Slowly, almost imperceptibly, sea surface temperatures had been increasing relative to the normal annual cycle along the equator since March, and the end of June found positive anomalies exceeding 1°C across broad expanses of the equatorial Pacific westward from the Ecuador-Peru coast to the Solomon Islands. Sea-level pressures fell slowly from April to May at the island stations of the eastern and central Pacific. Suddenly, from May to June, pressures in this area fell precipitously, while stations in Australia and Indonesia observed equally spectacular pressure rises.

These changes signaled a rapid weakening of the South Pacific anticyclone and a major swing in what meteorologists refer to as the "Southern Oscillation." By late 1982, the "Southern Oscillation Index," which is a measure of the sea-level pressure difference between the South Pacific High and the Indonesian-Australian Monsoon Low, reached record low levels. As sea-level pressures fell in the eastern Pacific and rose in Indonesia and Australia, the normal west-to-east pressure gradient along the equator weakened and then reversed. In response to this reversal, the easterly trade winds, which usually prevail throughout most of the tropical western Pacific, were replaced by equatorial westerly winds, which gradually spread eastward, past the Line Islands, into the eastern equatorial Pacific.

These pressure and wind changes were associated with dramatic shifts in the large-scale precipitation patterns over the entire tropical Pacific, which resulted in major socioeconomic and ecological disruptions. Month after month of subnormal precipitation resulted in widespread drought over Australia, Indonesia, Southern India, Sri Lanka, and large areas of the African continent south of the equator during the last half of 1982 and early 1983. In contrast, the islands of the western and central Pacific experienced day after day of torrential rainfall, with monthly totals several times the normal values. Christmas Island (Line Islands) experienced flooding unknown in the memory of the inhabitants. By October 1982, heavy rains and flooding had reached Ecuador and northern Peru.

The atmospheric developments were accompanied by major oceanic changes. Under normal conditions, the equatorial trade winds maintain a substantial gradient of sea-level along the equator, with higher water toward the west. When the equatorial trade winds collapsed in mid-1982, water surged eastward across the Pacific basin. In the western Pacific, sea-levels dropped, exposing fragile tidelands to the atmosphere. Meanwhile, rises in sea-level in the eastern Pacific brought flooding to tidal estuaries along the South American coast. The rises in sea-level could be tracked as they spread eastward across the Pacific along the equator and then northward and southward along the coast of the Americas, reaching as far north as the coast of British Columbia.

In September, the slow and somewhat erratic warming of the sea surface temperatures in the eastern equatorial Pacific suddenly accelerated. The appearance of warm waters (locally referred to as "El Nino") at this time of the calendar year had not been observed in over 40 years. Coincident with the sea surface temperature rises in the eastern Pacific, the thermocline, which divides the relatively warm layers of water near the ocean surface from the much colder water below, plunged to record depths, and upwelling of cold, nutrient-rich waters from below the thermocline was suppressed over a wide area. The impact on fisheries and wildlife was severe and widespread.

The dramatic changes in the rainfall distributions in the tropical Pacific resulted in large heating anomalies that, in turn, were accompanied by anomalies in the planetary circulation over much of the globe. The entire tropical troposphere warmed, and abnormally strong jetstreams appeared in both hemispheres. The intensification and southward displacement of the jetstream and the Aleutian low in the north Pacific were accompanied by the development of a succession of unusually deep cyclonic storms with central pressures below 950 mb. The abnormal pattern in the Pacific persisted throughout the 1982-1983 winter, and during January through March it was accompanied by large and persistent anomalies in circulation patterns over North America, which brought a sequence of intense storms ashore along the California coast, very heavy rainfall to the southeastern United States, and mild temperatures to western Canada and the northwestern United States.

The meteorological and ecological effects associated with the 1982-1983 El Nino/Southern Oscillation (ENSO) event directly affected the lives of hundreds of millions of people in diverse regions of the globe. It was clearly the strongest of nine such events that have occurred during the past 40 years, and it may well have been the strongest event of the century. It is perhaps equally significant that this was the first such event to be perceived by scientists not merely as a collection of diverse meteorological and oceanographic events that tend to occur in a preferred sequence, but as a single entity in which interactions between the tropical Pacific Ocean and the global atmospheric circulation can be interpreted in terms of concepts based on physical laws. It is this emerging physical understanding of the ENSO phenomenon that offers hope of predicting year-to-year fluctuations of the global climate system.

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