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an Ocean Climate Research Plan

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Environmental Research Laboratories
Boulder, Colorado

AN OCEAN CLIMATE RESEARCH PLAN

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Juanita M. Kreps, Secretary

NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION
Richard A. Frank, Administrator

Environmental Research
Laboratories
Wilmot N. Hess, Director

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Foreword

This document outlines a strategy for investigating the ocean's role in global climate fluctuations. The basic concept is that since oceanic and atmospheric circulations are tightly coupled, global climatic variations are manifested in ocean variations. These should exhibit significant coherence in time and space because of the large thermal and mechanical inertia of the ocean. Understanding the dynamics of large scale ocean variability will elucidate the relative roles of the ocean and atmosphere in forcing the behavior of the coupled system, the processes involved, and potential tools for predicting climate changes. But the ocean is so large and its behavior so complex that it can easily swallow up any finite amount of resources. To achieve maximum progress from limited resources, a research strategy is needed to guide the investment of effort. This document attempts to outline such a strategy in general terms, but with a rationale specific enough to derive priorities within the context of the overall problem. For particular investigations such as EPOCS, STREX, and a proposed study of ocean heat transport and storage, supplementary "Program Development Plans" (PDPs) have been developed which provide details of proposed activities, costs, schedules, etc.

So little is known of the dynamics of climate variability that tapping the wisdom of the scientific community and developing a consensus are particularly difficult and time-consuming tasks. The development of this document began in the summer of 1977 with a working group consisting of John E. Kutzbach, Chairman of the NAS Climate Dynamics Panel; W. Lawrence Gates, previous chairman of that panel; D. James Baker, NAS Ocean Sciences Board; and Uwe Radok of the Climate Office and Kent Groninger of the Office of Programs of NOAA's Environmental Research Laboratories. Over the past two years of evolution several drafts were widely circulated and valuable inputs were received from many people. Two workshops were held to provide forums for face-to-face discussions. The final product reflects in some measure all of these inputs and should not be viewed as the work of particular individuals.

During this period, a large number of other planning documents for climate research were prepared by various groups. Many of these contain ideas which have influenced this document, but two deserve special mention. They are "Elements of the Research Strategy for the United States Climate Program" (1978) and "The Continuing Quest" (1979) both published by The National Research Council, Washington, D.C. Together with this document and its corollary PDP's, we believe that these publications spell out a coherent and internally consistent research strategy, in increasing levels of detail, for understanding the dynamics of global climate through investigating ocean processes.

J. O. Fletcher
National Oceanic and Atmospheric Administration
Environmental Research Laboratories
Boulder, CO 80303

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AN OCEAN CLIMATE RESEARCH PLAN

EXECUTIVE SUMMARY

This document contains the rationale and recommended plan for a research program on the oceanic processes that underlie the dynamics of the global climate and its variability. The goal of the program is to identify and clarify the processes responsible for year-to-year climate change, and to apply the resultant understanding to the development of conceptual and numerical models for use in the simulation and prediction of climate.

It is important to understand the workings of the climate system for both social and economic reasons (Chapter 1). The climate affects us, and we affect the climate. We must know how and why in order to manage our resources properly now and to make adequate long-term plans. These points have been made forcefully and at some length in the United States Climate Program Plan and in the National Climate Act that President Carter signed into law in September 1978.

The ocean is a basic part of the climate system (Chapter 2). With its large heat capacity and energetic, slow variations, the ocean contributes strongly to the interannual and longer term variability of the atmosphere. Numerical models of the atmosphere and ocean used for long-term forecasts will have to incorporate the correct coupling of the atmosphere and ocean before they can simulate the known climate and predict future climate variations. In particular meteorologists need to know the patterns of evolution of the upper ocean temperature as a fundamental driving force for the atmosphere. At present, ocean climate processes are the least understood part of the climate system. An ocean climate program is needed to carry out the necessary research on ocean processes related to climate so that the evolving climate models can be realistic.

Recent severe winters and droughts in the United States have underscored the pressing national need to understand and predict year-to-year fluctuations of global climate. In addition, we must begin now to understand the effects of external and man-made factors such as CO_2 on the climate.

The U. S. Climate Program Plan and reports of both the U. S. National Academy of Sciences and the World Meteorological Organization have identified the priority areas for ocean climate studies. These reports point out that vigorous efforts to understand and predict large-scale ocean processes, utilizing new experimental and theoretical techniques perfected during the past decade, promise to provide a base for improved predictions. The oceanic information is to be gained through a parallel sequence of field experiments and study of historical data. The oceanic information will be translated into useful understanding through empirical and theoretical studies of dominant processes and the construction of numerical coupled ocean-atmosphere models. The reports recommend that first priority be given to the shorter climatic time scales: seasonal (annual) to year-to-year (interannual).

The Ocean Climate Program has two major initial objectives (Chapter 3):

- To identify and understand the oceanic processes responsible for heat advection and storage, the exchanges of heat between the ocean and the atmosphere, and their contribution to seasonal and interannual climate anomalies.
- To develop and test systems for establishing an instrumental network, together with satellite methods for transmitting information and for remote sensing from space, to provide observations of oceanic processes over prolonged periods, as a basis for understanding and predicting climatic fluctuations.

These objectives are to be met through a parallel set of studies described in Chapter 4 and elaborated in supplemental program development plans:

- Regional observational/theoretical studies of large-scale coupled processes in the ocean and atmosphere in the equatorial regions where coupling is strong and interannual variations are large.
- Observational/theoretical studies of the processes responsible for oceanic heat flux, its role in variations of the global energy balance, and associated global and regional climate fluctuations.
- Observational/theoretical studies of boundary layer transfers of heat, momentum, and moisture between the ocean and the atmosphere (especially in stormy conditions) for parameterization into numerical models.
- Observational/theoretical studies of the processes responsible for the variability of the distribution of sea ice and its effect on seasonal and interannual changes of the polar albedo and air-sea interaction.
- Observational/theoretical studies of the mechanisms of vertical and horizontal geochemical exchanges in the ocean, with special attention to the partitioning of CO_2 between ocean and atmosphere.
- Development of new instrumentation systems and utilization of satellite remote sensing for the observation of large-scale long-term changes in the ocean, and of working agreements on maintenance of long-term monitoring.

All these topics are interdisciplinary, coupling oceanographic with meteorological concepts and investigations. However, two of them belong to wider frameworks: the ice-ocean interaction studies form part of the international polar research program on climate as set out in GARP Publication No. 19 (GARP, 1978a), while the geochemical exchange studies have strong links

to biology and geology and to projects concerned with estuaries, coastal zones, and the sea floor (Center for Ocean Management Studies, 1977). Therefore these two topics are treated only in outline in this research plan.

Through these studies of climatic factors and the establishment of a climate monitoring system, we should also obtain new and increasingly global views of the ocean and its variables. In addition to its application for climate prediction, such information forms the basis for climatic advice to users of the ocean, the fisheries industry, merchant shipping, and the Navy.

No one organization possesses all the resources and expertise needed to carry out such a program (Chapter 5). Therefore the overall program must include contributions from government agencies, universities, and oceanographic institutions. The primary national coalition of ocean climate studies includes the National Oceanic and Atmospheric Administration (NOAA), National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), and Department of Defense (DOD). Pioneering ocean climate efforts have been made in two programs of the National Science Foundation (NSF): Climate/Long Range Investigation, Mapping, and Predictions (CLIMAP), and North Pacific Experiment (NORPAX), which is also supported by the Office of Naval Research (ONR).

A summary of planned and recommended oceanographic and atmospheric studies is given below; plans for work on ice-ocean interaction and geochemical exchanges can be found elsewhere (GARP, 1978a, and Center for Ocean Management Studies, 1977).

OCEAN CLIMATE PROGRAM SUMMARY

PROJECT 1: EQUATORIAL SST ANOMALIES

Objectives	Role of variable equatorial forcing in regional and global climate fluctuations.
Problem, Nature	The comparable response times of ocean and atmosphere in the equatorial zone create high SST variability and strong coupling with the atmosphere. The processes responsible involve complex currents and waves in the ocean and interactions on a wide range of scales in the tropical and extratropical atmospheres.
Research Strategy	Regional field projects in each of the tropical oceans. Analysis of historical and continuing observations (especially from satellites) for periods of contrasting SST anomalies.
Program	Field measurement coordination with EPOCS, NORPAX, and the equatorial components of FGGE. Shuttle-type flight measurements of hydrographic parameters and boundary layer exchanges. Modeling of SST anomaly creation by internal waves and zonal flow instability. Rainfall estimation from satellite data. Empirical studies of ITCZ structure and interactions between tropical and extratropical weather systems. EOF and EPOCS analyses of historical ocean/atmosphere records.

PROJECT 2: OCEAN HEAT FLUX: SUBTROPICAL GYRE DYNAMICS

Objectives	Western boundary current fluctuations, gyre processes, and the Antarctic Circumpolar Current (ACC) as elements of the ocean heat transfer.
Problem, Nature and Difficulties	Gulf Stream and Kuroshio fluctuations form a major and readily monitored aspect of ocean variability. Gyre processes and the ACC at present defy comprehensive study, and their contribution to ocean heat transport must be inferred from focused cruise data and buoy measurements.
Research Strategy	Frequent and continuing measurements of Gulf Stream characteristics; systematic sampling along gyre cross section; process studies at gyre boundary and in the ACC.
Program	Measurements of Gulf Stream flow rates, temperatures, salinities, across Florida Strait. Series of hydrographic cruises across the Atlantic along 24°N and 26°N. Studies of upwelling and vorticity input along southern edge of subtropical Atlantic gyre, and of water mass production and abyssal flow south of New Zealand. Interpretation, modeling, planning of further sampling projects.

OCEAN CLIMATE PROGRAM SUMMARY (continued)

PROJECT 3: STORM TRANSFER AND RESPONSE

Objectives	Parameterization of ocean-atmosphere fluxes in strong winds.
Problem, Nature and Difficulties	Existing knowledge is limited to light-wind conditions; storm transfers are not readily measured but probably dominate overall air-sea interaction.
Research	From observations on a number of similar storms evolve composite series describing time changes of various elements and fluxes during typical storm passage.
Program	Field measurements near weather station "PAPA" (50°N, 145°W): NOAA ship, aircraft, moored and drifting buoys, synoptic and satellite data. Compositing of measurements and parameterizations in terms of relative location, time during passage, storm characteristics. Use of parameterizations in NWP models to match individual storms and stochastic effects of storm ensembles.

PROJECT 4: OCEAN MEASUREMENTS

Objectives	Techniques for large-scale and long-term ocean observations.
Problem, Nature and Difficulties	Measurements of bulk ocean properties are urgently needed to define its role in climatic fluctuations. Special techniques must be developed to ensure representativeness and continuity of the measurements.
Research Strategy	Development and testing of experimental systems. Critical appraisal of oceanographic products obtained by remote sensing from satellites.
Program	Deep pressure gauging (with guidance from tsunami warning system experience). Recording of vertically and horizontally averaged deep currents with bottom-mounted electric field measuring systems (modified for long-term use). Current measurements with acoustic Doppler shift systems. Remote satellite sensing of ocean surface. Remote lidar sensing of surface layer properties.

ABBREVIATIONS USED IN THE PLAN

AOML	Atlantic Oceanographic and Meteorological Laboratories, ERL/NOAA
CIMAS	Cooperative Institute for Marine and Atmospheric Studies, NOAA and University of Miami
CLIMAP	Climate/Long Range Investigation, Mapping, and Predictions
DOD	Department of Defense
EDIS	Environmental Data Information Service, NOAA
EPOCS	Equatorial Pacific Ocean Climate Studies of ERL/NOAA
ERL	Environmental Research Laboratories, NOAA
FGGE	First GARP Global Experiment
GARP	Global Atmospheric Research Program
GATE	GARP Atlantic Tropical Experiment
GCM	General Circulation Model
GFDL	Geophysical Fluid Dynamics Laboratory, ERL/NOAA
IIOE	International Indian Ocean Expedition
INDEX	Indian Ocean Experiment
IOC	Intergovernmental Oceanographic Commission
JASIN	Joint Air-Sea Interaction Experiment
MILE	Mixed-Layer Experiments
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research, NSF
NCC	National Climatic Center, EDIS/NOAA
NESS	National Environmental Satellite Service
NODC	National Oceanic Data Center, NOAA
NODS	National Oceanic Data Service, NOAA
NORPAX	North Pacific Experiment
NRC	National Research Council
NSF	National Science Foundation
ONR	Office of Naval Research
OOE	Office of Ocean Engineering, NOAA
PMEL	Pacific Marine and Environmental Laboratory, ERL/NOAA
POLYMODE	Polygon Mid-Ocean Dynamics Experiment
RFC	Research Facilities Center, ERL/NOAA
SCOR	Scientific Committee for Ocean Research
SST	Sea surface temperature
STREX	Storm Transfer and Response Experiment
WMO	World Meteorological Organization, U.N.
WPL	Wave Propagation Laboratory, ERL/NOAA

AN OCEAN CLIMATE RESEARCH PLAN

1. INTRODUCTION

The Ocean Climate Program is a contribution to the search for a better understanding of climate change and its impact on our daily lives. The need for governments to recognize and anticipate climate fluctuations and their domestic, national security, and international impacts and to identify potential human impacts on regional and global climate has been documented in some detail in "A United States Climate Program Plan" (Federal Coordinating Council for Science, Engineering, and Technology, July 1977). That plan provides a framework for the coordination and pursuance of Federal activities in the broad field of climate. The National Climate Act was signed into law by President Carter in September 1978.

Over the last five years intensive efforts have been made by the national and international scientific community to assess the climate problem and define a research strategy. The results of these efforts are summarized in three basic documents:

Understanding Climatic Change (National Academy of Sciences, 1976).
The Physical Basis of Climate and Climate Modelling (GARP, 1975).
Elements of a Research Strategy for the United States Climate Program
(National Academy of Sciences, 1978).

Interannual variations in atmospheric circulation (i.e., climate variations) arise from changes in the geographical pattern of thermal forcing of the atmosphere. Probably the largest factor in this forcing is the temperature of the upper ocean. This document focuses on investigation of the processes causing the variations in sea surface temperatures (SST) and the associated variations of the atmosphere.

The weather patterns on an Earth without oceans (but with a sufficiently moist surface), would have fluctuations on year-to-year and even longer time scales. Such fluctuations would reflect only the inherent instabilities of the atmosphere.

The existence of a large, deep ocean which absorbs and transports most of the solar heat adds another controlling factor to the lower boundary of the actual atmosphere. This new factor could make our existing climate system more predictable than that of the hypothetical no-ocean Earth in the following way. The ocean stores vast amounts of heat with only small changes of temperature beneath its surface. It can then give the heat slowly back to the atmosphere, over long periods of time and at different places. This advection, storage, and transfer of heat to the atmosphere provide a slowly varying driving force for the atmosphere. Empirical studies have shown suggestive correlations between sea surface temperature changes and subsequent climatic fluctuations. Thus it is possible that a major part of atmospheric fluctuations on year-to-year time scales is related to such slowly varying oceanic

driving forces. Prediction of interannual atmospheric changes then becomes a problem of predicting interannual oceanic changes, a problem which may be easier due to the inherently long time scale of response of the ocean compared to the atmosphere. In any case, it is clear that an understanding of the oceanic processes which produce heat and advection, storage and transfer of heat to the atmosphere is fundamental to the understanding of interannual climate change.

The Ocean Climate Program is focused on that issue. Even with this focus, however, the program embraces much of physical and chemical oceanography. In the end we will require fundamental understanding of heat transport in the ocean, air-sea exchange processes under all conditions and on all scales, ocean-ice-air interactions in the polar regions, and geochemical mixing and exchange. This understanding will require an observational system which will lead us toward the establishment of a global oceanic observational network. Developing and testing the observational systems necessary for the establishment of such a network is a crucial step towards our ability to keep a finger on the interannual pulse of the oceans.

En route to this understanding and the establishment of a monitoring system, we shall obtain new and increasingly global views of the ocean and its variables. Such information is useful in itself, for it forms the basis for appropriate climate advice to users. Such users include the fisheries industry, which has noted for years the relation between fluctuations of fisheries stocks and ocean variables such as temperature and salinity; ocean merchant ships, which use current information for navigation; and the Navy, which needs such information for national defense.

The program plan is organized into four chapters. Chapter 2 is a review of the role of the ocean in the dynamics of climate. Chapter 3 summarizes the research strategy for climate studies recommended by the National Academy of Sciences (through the Climate Dynamics Panel of the U. S. Committee for the Global Atmospheric Research Program). Priorities for the ocean are emphasized. Chapter 4 is the heart of the program plan; it formulates specific goals and objectives and the major program components. Chapter 5, a possible organizational framework for national and international planning and coordination, completes the plan.

Much of the information we now have on ocean climate has resulted from the numerous studies over the past few years on the interaction of the Pacific Ocean and the overlying atmosphere by investigators associated with the NORPAX program (supported by the Office for the International Decade of Ocean Exploration of the National Science Foundation and by the Office of Naval Research). NOAA has now begun to complement the NORPAX equatorial studies with its own EPOCS project. The Ocean Climate Program is an attempt to broaden this ocean research and encourage the transfer of climate understanding into operational climate models.

2. THE ROLE OF THE OCEAN IN CLIMATE DYNAMICS

The World Meteorological Organization, in the document entitled "The Physical Basis of Climate and Climate Modelling" (GARP, 1975), has pointed out that (emphasis added):

In trying to understand the mechanisms that create the earth's climate and its variations, we are faced with an enormously complex physical system, which includes not only the relatively well-known behaviour of the atmosphere, but also the less well-known behaviour of the world's ocean and ice masses, together with the variations occurring at the earth's surface. In addition to physical factors, there are complex chemical and biological (feedback) processes affecting the climate, which are also of importance for the climate's impact on living things and thus on man....

Each of these processes undergoes complex interaction with some of the others over a wide range of space and time scales, extending from the small-scale processes which occur about us daily to those embracing the entire earth and lasting many years. The task of sorting out climatic cause and effect in a rational way from this complexity has only just begun. This constitutes the scientific challenge that we must accept if we are to develop a satisfactory theory of climate. In this quest the mathematical modelling of climate will play an essential role, for only through such an approach can we hope to achieve the necessary quantitative understanding....

On seasonal, annual and decadal time scales, climate models must take into account an interactive upper ocean and sea ice, changes in the atmospheric composition and aerosol loading, and biological changes in the character of the earth's surface. On long time scales, (e.g., 100 to 1000 years) consideration must be given also to changes in the deep ocean and to the variations of the continental ice sheets....

The fluxes of most physical properties across the air-sea interface are determined by the conditions at the interface itself with the exception of precipitation. These conditions, the most important being the sea surface temperature, are themselves determined by the dynamics of the coupled ocean-atmosphere system. Although many of the dynamical and thermodynamical feedback processes involved are not well understood, the role of the oceans is believed to be a dominant one on climatic time scales. This is because of the large thermal and mechanical inertia of the sea resulting from its relatively high heat capacity and from the long time constants of the sub-surface and deep circulations. The turnover of deep and intermediate waters is also a governing process in the uptake of CO₂ by the ocean....

Apart from its direct dynamical and thermodynamical role in the coupled ocean-atmosphere system, the internal climate of the sea

itself is an important factor in other processes, e.g., in relation to biological productivity. In addition, the distribution of chemical and other tracers in the deep sea and sedimentary processes represent valuable records of past climates....

The main properties of the ocean that are important in climate have been well summarized by Hamon and Godfrey (1975; see also Hamon and Godfrey, 1978) as follows:

- The area of the ocean is large relative to that of the land. This difference is particularly marked in the Southern Hemisphere, where the oceans account for about 85% of the surface area (compared with 61% for the Northern Hemisphere). Additional relevant features in the Southern Hemisphere are a major ice cap, and large and variable sea ice cover.
- The oceans are cold (average temperature 3.5°C), and have a large heat capacity relative to the atmosphere. The heat capacity of the upper three metres of the ocean is equivalent to the total heat capacity of the atmosphere. Comparing the oceans and the land, the main reason for a difference in effective heat capacity is due more to the difference between a liquid and a solid than to a difference between specific heats. The upper 50 to 100 metres of the ocean are well stirred, so that their alteration in temperature for a given change in heat input is very much less than the change in surface temperature on land.
- The oceans are stratified, at least in tropical and temperate latitudes, where one finds a thin (a few hundred metres) warm surface layer. The stratification is stable in these latitudes so that the main bulk of the ocean (the cold waters below a few hundred metres depth) is isolated from the atmosphere, except when very long time scales are considered.
- Due to its high heat capacity and slow currents, the ocean changes slowly compared to the atmosphere. Diurnal heating and cooling in the open ocean is generally not directly measurable. The seasonal variations are confined to the upper few hundred metres. In regions of strong currents, away from the equator, even the seasonal variations may be overshadowed by temperature fluctuations due to passage of eddies.
- The oceans are the main source of atmospheric moisture. The average evaporation rate is about 100 cm per year. The range is between 10 and 150 cm per year, depending mainly on latitude. These figures, of course, are long-term averages; the actual evaporation rate at any given place and time depends very markedly on season and weather, and is an important factor in the complex and vital feed-back process between atmosphere and ocean.

The main features of the surface in the upper 50 m of the ocean currents are fairly well known. Most historical information about surface currents has come from analyzing the information obtained from the navigation of ships.

Maximum values for surface currents are about 200-250 cm/s. From other sources, it appears that in most places these strong surface currents decay rapidly with depth, falling to about half their surface value at 300 m depth.

At the surface, the currents in the tropics are mainly westward. At the western sides of each ocean basin, the currents turn poleward, becoming the narrow, strong features called "western boundary currents" (e.g., the Gulf Stream). At higher latitudes, currents are generally eastward. A broad, weak equatorward flow in the middle and east of each basin, at mid-latitudes, completes the surface circulation. We can summarize this description of the mean surface flow by saying there is an anticyclonic (clockwise in the Northern Hemisphere, anticlockwise in the Southern Hemisphere) "gyre" in each main ocean basin.

In the Southern Hemisphere, the Antarctic Circumpolar Current is a special feature, with no counterpart in the Northern Hemisphere.

The main oceanic currents are shown in Figure 2.1. Like the above description, this diagram gives only the main long-term average features. As in the distinction between "weather" and "climate" in the atmosphere, the oceans show quite complex and ever-changing circulation patterns when looked at in more detail. Very common features appear to be eddies of diameter about 300-500 km, with surface currents up to 1200 cm/s.

From the oceanographer's point of view, ocean currents are driven mainly by wind stress, and to a lesser extent by density changes caused by heat and water exchanges with the atmosphere. The primary effect of wind is to set up an "Ekman" transport within the top 100 m. This water transport is to the right of the wind in the Northern Hemisphere. Variations in wind pattern produce convergences and divergences in the Ekman layer. The observed surface (and deeper) currents to a large extent are a secondary effect of the convergences and divergences. It should be mentioned that the primary Ekman transport is difficult to observe, and that more complex effects (e.g., "Langmuir cells", cf. Assaf et al., 1971) have been observed.

Langmuir cells may appear within minutes of the onset of wind, whereas the Ekman transport takes about a day to develop. The main features of ocean surface current "weather" can be portrayed in terms of the "dynamic height" of the sea surface (Fig. 2.2)--essentially pressure, expressed as centimeters of water--obtained from the measured water density distribution and the hydrostatic assumption, and assuming deep flow to be slow. High surface dynamic heights correspond to regions of warm, light water. Currents flow along "isobars" of constant dynamic height, in the direction of the arrows.

It is important to note the different time scales of such surface phenomena. The patterns in Figure 2.2 have a typical time scale of about 100 days, though an individual eddy might last 6-12 months (as against time scales of about 5-10 days for comparable features in the atmosphere). The main ocean gyre circulations have time scales of a few years -- this is the time for a parcel of water to make a complete circuit of the gyre, and also an estimate of the time it would take for such a gyre to decay because of friction, if driving forces were removed. Close to the equator, however, major current features sometimes appear to change more rapidly.

Figure 2.1.--Major surface currents of the world (Northern Hemisphere winter). From Bowditch (1966).

Figure 2.2.--Ocean surface "weather" off the coast of Australia, 8 November to 4 December 1960. The contours give the dynamic height sea surface from which the ocean currents can be determined by a relation similar to that linking atmospheric pressure and wind. (After Hamon and Godfrey, 1975).

The movements of water in the deep ocean (2000-5000 m) are not well known or understood. Earlier ideas that these deep waters are formed by sinking of surface water near Antarctica (mainly in the Weddell Sea) in winter have been shown by POLYMODE to be oversimplified. However, an estimate of residence time for the deep water can be made by dividing its volume by the estimated rate of formation; the result (~ 1000 yr) is confirmed by results of chemical and radioactive tracer studies.

These structural elements and features of the ocean play a number of climatic roles. Each role is important to climate, and none is sufficiently well understood to allow us to predict reliably what might happen as other variables change.

In the tropical regions, the ocean-to-atmosphere coupling appears to play a dominant role in short-term variability of the atmosphere. Monthly to interannual sea surface temperature (SST) variability is high in the tropics (Fig. 2.3), and models of the atmospheric general circulation show a high sensitivity to oceanic conditions near the Equator, where warm ocean anomalies may directly influence equatorial rainfall (Fig. 2.4). Variations in the distribution and intensity of tropical rainfall are widely believed to provide a "climatic signal" for the rest of the globe. Models and observations of tropical ocean variability suggest a large-scale coherence, consistent with the idea that low-frequency changes in the trade winds induce transients in the transport of currents in the central tropical ocean (Fig. 2.5). These transients, in turn, result in thermal anomalies, such as El Niño in the eastern tropical Pacific or upwelling in the Gulf of Guinea in the eastern tropical Atlantic. The redistribution of heat by ocean currents appears to be the primary mechanism in the establishment of large-scale oceanic heat anomalies both in the central equatorial ocean and along the eastern boundaries.

Figure 2.3.--Monthly average sea surface temperature (SST) anomalies in the equatorial Pacific, 1971-73. The changes from dark blue to dark red or vice versa amount to more than 8°F. Positive anomalies are red, negative are blue.

Figure 2.4.--Air and sea surface temperatures and rainfalls at Canton Island, 1956-67. Bjerknes (1969) used these data to illustrate a possible meteorological effect of equatorial SST anomalies; for an alternative interpretation see Ramage (1977).

Figure 2.5.--(A) Annual running means of the sea level difference across the equatorial countercurrent (after Wyrtki); (B) Corresponding values of the strength of the subtropical 700 mbar westerlies as measured between 150°E to 110°W and 20°N to 35°N (from Namias, 1973, with permission of the author and the publisher; copyright 1973 by the American Association for the Advancement of Science). The peaks and troughs of the upper wind speed curve (B) frequently occurred slightly before those of the speed of the countercurrent (as given by the meridional slope of the sea surface, curve A).

But the physical link back to the trade wind behavior remains obscure, although a meridional (Walker) circulation linking the atmospheres over the eastern and western Pacific has long been accepted as proven by statistical analyses of air pressure and other meteorological data.

In the Indian Ocean, equatorial ocean studies are particularly important. The Indian Ocean monsoon is the strongest large-scale, long-period variable forcing that the atmosphere exerts upon the ocean, and the variability of major Indian Ocean currents (e.g., the Somali Current) is the most pronounced in the world. Moreover, evidence is accumulating that links sea-surface temperature anomalies with the anomalies in rainfall over India. Modeling suggests that, in certain cases, higher sea temperatures in the Arabian Sea could cause greater precipitation over India.

The surplus heat gained in the tropics is carried by the atmosphere and the ocean toward the poles. Recent determinations of the Earth's heat balance from satellite-measured radiation fluxes outside the atmosphere, and from an evaluation of atmospheric meridional heat fluxes from upper air measurements, have shown that the ocean is left to carry a large share of the meridional heat flux needed for global balance. Figure 2.6 shows the relative magnitude of these two transports: at 20°N the ocean carries 75% of the total and the atmosphere only 25%; in the Southern Hemisphere the ocean heat transport is larger than that of the atmosphere to 30°S and remains substantial even in 60°S .

Figure 2.6.--Variation of energy transports with latitude in the Northern Hemisphere (Vonder Haar and Oort, 1973) and Southern Hemisphere (Trenberth, 1979). A perspective of magnitude is provided by the energy of a mid-latitude depression, $\approx 10^8$ MW. The ocean share of the heat transport, determined as the residual needed to balance the global budget, is larger than that of the atmosphere in low northern latitudes, and remains substantial in high southern latitudes.

In order to properly incorporate oceanic heat flux into global numerical models a better understanding is needed of how the heat is actually transported. At present we do not know how or where the heat is transported in the ocean, but the following types of heat transport all are potentially important: transport by the mean circulation in horizontal gyres; transport by the mean circulation in vertical meridional cells of the abyssal circulation; transport in the surface layers of the ocean; transport by eddies; and water mass formation. A series of pilot experiments on these different mechanisms will be required to gain the information necessary for launching a program for monitoring the poleward fluxes.

In mid-latitudes, heat is transferred from the ocean to the atmosphere. Off the east coasts of Asia and North America the thermal gradients at the cold boundaries of the warm western boundary currents create strong horizontal differences in the heating of the lower atmosphere. This is reflected in a persistent deformation of the mean upper wind field: the temperature contrasts induce thermally direct mean meridional circulations, which strengthen the polar jet streams, especially in the Northern Hemisphere winter. As a consequence storms moving across the North Pacific and Atlantic tend to intensify near the Kuroshio Current and Gulf Stream.

Figure 2.7 dramatically illustrates the effect of this thermal gradient on the variance of the meridional wind component over periods of 2.5 to 6 days, the spectral region which can be identified with developing baroclinic disturbances. Displacements of the current boundaries and the corresponding anomalies of heat storage and sea surface temperature could be related to atmospheric circulation anomalies. The processes which link the ocean surface

Figure 2.7.--Variance of the meridional wind component in the 2.5- to 6-day time range (Blackmon et al., 1977). The paths of the Gulf Stream and Kuroshio Current are indicated by the broken lines and coincide with the regions of maximum atmospheric variability.

temperature and bands of strong baroclinicity with the storm tracks must be clarified if we are to understand the basic dynamics of the atmosphere.

The pioneering work of Namias in finding correlations between patterns of sea surface temperature anomalies in the eastern and central Pacific and atmospheric patterns of 700 mb height, storm intensities, and storm tracks is a step in this direction. For a deeper physical understanding the detailed reaction of the ocean surface layers to, and their effects on, individual weather systems must be clarified. A crucial part of such understanding

Figure 2.8.--Changes in average boundary fluxes during five frontal passages over the southern ocean (from Zillman, 1972, with permission of the author and the publisher; copyright 1972 by the American Geophysical Union). The ocean surface loses much more sensible and latent heat in the colder and drier southwesterly stream behind the front than in the warmer and moister pre-frontal flow from the northwest.

concerns the formation and deepening of the mixed surface layer and its interactions with the atmosphere. Such processes occur over areas smaller than the grid squares used by modelers--they are "subgrid scale". Their parameterization in terms of large-scale variables is required and is unlikely to be simple.

Measurements of surface stress, evaporation, and heat transfer have so far been largely limited to low wind speeds, whereas much of the transfer probably occurs at high wind speeds. Moreover, the static stability of the atmospheric boundary layer strongly affects vertical transfers. For these reasons, vertical transfers over the sea change dramatically with the passage of a cold front (Fig. 2.8). This suggests a research strategy for assessing the course of air-sea exchanges of momentum, heat, and water vapor, and for studying the changes of the boundary layers of the atmosphere and ocean during the passage of storms. Such a program should be carried out in a region of high thermal gradient, i.e., in the vicinity of a western boundary current or its extension region.

The heat flux and sea surface temperature anomaly problems are linked in the polar regions, where the prime climatic processes are those that control the extent and concentration of the sea ice (GARP 1978a). The large albedo and insulating effects of sea ice have a significant impact on the heat balance of the polar regions and produce a strong seasonal signal. For example, the effective size of the Antarctic continent roughly doubles as the sea ice expands from fall to spring. In the Arctic, interannual variability of the ice cover is about one-half the mean annual change.

But in spite of our increasing ability to monitor the changes in extent and concentration of the ice, we know very little about the processes that control those changes. The upper ocean is a major determining factor, because the heat supplied from below influences whether the ice freezes or melts. A second factor in polar regions is the amount of ice carried by the surface currents. For example, in the Arctic the amount of ice carried out of the Arctic basin east of Greenland is as important in the overall regional heat budget as the amount of heat carried by the ocean currents. We need both upper ocean experiments carried out in the vicinity of the ice edge and more modeling of the processes. In particular, we need understanding and parameterizations of ocean/atmosphere heat and moisture exchanges over mostly ice-covered seas, as functions of the fraction of open water and the air trajectory (especially around Antarctica).

Geochemical exchanges in the ocean are also important to climate. The report Studies in Geophysics: Energy and Climate of the National Academy of Sciences (1977) has noted that success in estimating future atmospheric CO₂ levels depends, among other things, on being able to estimate the fraction of CO₂ released by the burning of fossil fuel that is taken up by the ocean. Further field and theoretical studies are necessary in order to improve the one-dimensional ocean exchange and mixing models now used for determining how excess CO₂ is partitioned between the ocean and the atmosphere and the transfer processes involved.

3. OVERALL RESEARCH STRATEGY

An overall research strategy for the U.S. Climate Program has been recommended by the Climate Dynamics Panel of the U.S. GARP Committee of the National Academy of Sciences/National Research Council. The report (National Academy of Sciences, 1978) notes that two lines of research activities are anticipated: individual and small group efforts and collaborative, focused efforts of larger groups. The individual efforts will be relatively low in cost compared with large collaborative efforts, but may provide crucial ideas and insight. Such efforts are expected to be a part of the studies described in the next chapter, but our focus in this report is on the large collaborative efforts which need substantial, continuing commitment and support for success.

Regarding time scales the Climate Dynamics Panel report notes that the present and anticipated near-future global observing system is best suited for detailed studies of the annual (seasonal) cycle of the atmosphere and its lower boundary. Since the annual cycle of the ocean is poorly understood, new

observational systems need to be developed to define it and to study the interaction on the annual scale between the ocean and the atmosphere. The ocean differs from the atmosphere in that its interannual response, in some regions at least, is the same order of magnitude as the annual response. Therefore the priority time scales for the ocean studies are monthly to inter-annual. All of the studies listed in the next chapter fall into this category.

The overall strategy should also include long period studies based on the use of non-instrumental records that span the entire several million-year geologically recent history of the Earth. These studies of tree-rings, land pollen, ocean sediments and ice cores help to define the climate characteristics of earlier periods, for example, glacial-interglacial fluctuations. In terms of the objectives of the Ocean Climate Program, it is important to note that knowledge of the climate response over long time scales can also provide useful information about shorter-term climate sensitivity. Moreover, a knowledge of past climates provides a data base for model validation, e.g., for assessing how well a climate model simulates a past climate, and how reliably a model reproduces past climate variations.

3.1 Four Main Areas of Study

The report of the Climate Dynamics Panel notes that focused efforts of groups of scientists are needed in the following four areas:

- Development of a climate data base.
- Definition and conduct of process/regional experiments.
- Development, validation, and evaluation of comprehensive climate models.
- Development of a climate observing system.

We shall consider each of these in turn. Improvement of the present instrumental climate data base is possible in the next few years and thus has a high priority for immediate action. Many of the data sets needed for climate research will also provide climate information for user applications. Therefore, efforts invested in this area should yield immediate as well as long-term benefits.

Process/regional experiments are needed to understand basic climate processes so that they can be properly parameterized in climate models. In the next chapter we outline those process experiments in the ocean on which there is broad agreement that (1) substantial progress can be anticipated with existing experimental and theoretical tools and (2) qualified people are available to do the research, given sufficient funding.

Climate models represent the ultimate tool for verifying our level of understanding, conducting studies of the sensitivity of the climate to various factors, and studying predictability. Modeling studies also aid in designing and simulating future observing systems and observing system components. Each of the studies discussed in the next chapter includes a modeling component that should be given a firm foundation by empirical studies of historical data. Most of our understanding of the climate system has come from empirical studies, which have opened the way to a program with a strong complement of

field studies and confident modeling goals. Empirical studies are highly cost-effective; a vigorous program using the most recent and complete data should be included in the Ocean Climate Program as a base for every modeling effort.

A climate observing system is required to provide long-term records of temporal climate variability. For many climate variables, including most ocean variables, our knowledge of what constitutes a significant variation over a particular time and space scale is not sufficient to permit the design of an optimum monitoring system now. Therefore, an experimental observing project is needed. The development and operation of a global observing system are tasks that must involve collaboration among many nations. Table 3.1 gives a tentative schedule from the report of the Climate Dynamics Panel (National Academy of Sciences, 1978).

3.2 Ocean Studies of Highest Priority

Ocean studies are prominent in each of the four categories mentioned above. For the rest of this report, which focuses on interannual variability, we will condense those four categories into two: (1) the study of processes contributing to interannual variability, using a climate data base, process/regional experiments, and climate models, and (2) development of an ocean climate observing system.

The U.S. Climate Program Plan and reports from both the U.S. National Academy of Sciences and the World Meteorological Organization have identified the priority areas of study of ocean processes leading to interannual variability. The five major areas of study are listed below:

Large-scale coupled ocean-atmosphere processes in the equatorial regions. Ocean response may be more rapid and hence more strongly coupled to the time scales of atmospheric driving in the regions near the Equator. Empirical studies show significant correlations between ocean variables and atmospheric fluctuations. A large body of data and expertise gained over the past years is a strong base for a concentrated program in this region, which must address all mechanisms transforming the effects of oceanic anomalies into large-scale atmospheric anomalies and vice versa.

Ocean heat flux. Calculations using satellite and atmospheric data suggest that, at low latitudes, the ocean carries the larger part of the heat necessary for the global balancing of the incoming solar radiation. Changes in this heat flux could have major implications for the terrestrial energy balance. There are many possible ways in which that heat could be transported in the ocean, but we do not know which is dominant. A better understanding of how the heat is actually transported is needed.

Air-sea transfers in storms. The boundary layer exchanges between sea and air must be understood and parameterized in terms of large scale variables. Past measurements of the transfers have been limited to low wind speeds, whereas much of the transfer probably occurs at high wind speeds. Climate models need the parameterizations, and the proper observational techniques are available.

Table 3.1.--Tentative timetable for development of the global observing system*

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

*National Academy of Sciences (1978).

Ocean-ice interaction. The size and concentration of the sea ice cover determine the amount of radiation reflected and the sensible and latent heat transferred to the atmosphere from the ocean in the polar regions. These ice features are determined by an interplay between the ocean, the ice, and the atmosphere. Parameterization of ocean-ice processes is needed for complete climate models.

Geochemical changes. The mechanisms for vertical mixing in the ocean are poorly understood; as a consequence, our knowledge of how much CO₂ the ocean can absorb, for example, is poor. Parameterizations of these chemical processes are needed for climate models.

The various reports all agree that efforts should start now on the long-term task of developing techniques for observing the ocean's three-dimensional structure and behavior. The first need is a mix of experimental observing programs, each of which will be relatively limited, but the sum of which will produce useful data and thus be cost-effective. The second need is for support of long lead-time tasks to develop techniques for observing the ocean's structure and behavior. The main priorities are a long-term commitment to measurements in a relatively few regions to be chosen on the basis of the best estimate of their dynamical importance, and an increasing exploitation, together with critical appraisal, of the oceanographic information provided by satellites.

4. THE PROGRAM PLAN

In this section we address the specific elements of the ocean climate program designed to explore the problem areas discussed in Chapter 3. Successful completion of such studies will significantly aid the construction of realistic models of coupled ocean-atmosphere circulation on climatic time scales. The highest priorities are to understand the processes responsible for advection and storage of heat in the ocean, for the exchange of heat with the atmosphere, and for its transfer to the synoptic-scale weather systems which collectively determine the state of the climate. All these studies concentrate on time scales up to and including the interannual.

We will not attempt here to lay out and justify details of the program elements. That will be done in the program development plans for each of the components. Instead each problem is defined and described from its current understanding, and the initial objectives of each study are set forth.

4.1 Process/Regional Studies

4.1.1. Equatorial Dynamics

Studies of the equatorial air-sea interaction problem have high priority among ocean climate regional studies. Fifteen years of experimental and theoretical exploration confirm that the ocean can respond rapidly to external forcing in the region bounded roughly by latitudes 7°N and 7°S. Major changes in the density and heat content of the ocean in mid-latitudes occur primarily

on time scales longer than about one year, but in the equatorial regions responses can be of the order of days to weeks although long-term changes also are observed. The short equatorial time scale overlaps with the time scales of major atmospheric disturbances, and thus a direct ocean-atmosphere interaction is possible.

The Climate Panel of the U.S. GARP Committee has pointed out a second aspect of the problem: while current numerical models of the atmosphere show relatively little response to mid-latitude thermal anomalies in the ocean, they do show a measurable response to equatorial anomalies of realistic magnitude. Thus a focus on the equatorial dynamics of thermal anomalies, and their coupling to the ocean below and the atmosphere above, will provide useful input to numerical climate models.

Finally, the response in the ocean near the equator is confined by a "wave-guide" effect derived from the variation of the Coriolis Parameter. This confinement has two obvious consequences. First, it means that most measurements also can be confined latitudinally, simplifying the logistics of field experiments. Away from continental boundaries, equatorial disturbances on many time scales can apparently propagate zonally and vertically but not meridionally. The second consequence is that energy inputs into the equatorial regions are focused, leading to strong and sometimes dramatic effects. If current ideas are correct, then El Niño is the result of an accumulation of energy that has propagated along the equator toward the coast of South America, producing large climatic and biological changes there. The economic impact of El Niño through reduced output from the Peruvian anchovy fisheries is well known.

The central goals of equatorial ocean climate studies are to investigate the complex equatorial ocean current system, including its driving forces and interactions with the large-scale atmospheric circulation, and to discover precursors that have predictive value for climate.

Initially the equatorial program will be focused on time-dependent motions of short period, monsoon response, eastern and western boundary effects, mean current systems, and the effect of all of these on thermal anomalies. Such work will require studies in all three oceans, since the atmospheric forcing and oceanic response are different in each.

Planned equatorial studies include:

- field experiments defining the time and space structure of the ocean current systems, temperature and salinity, together with surface winds and precipitation.
- modeling of processes of upwelling, waves, and advection, which determine the horizontal and vertical fluxes of heat and momentum in the atmosphere and ocean at the equator.
- identification of empirical relationships among oceanic and atmospheric variables in the equatorial regions using historical and continuing long-term observations.

Field Experiments. A number of studies over the past 15 years have been carried out in the equatorial regions of all three oceans. These include IIOE and INDEX in the Indian Ocean, GATE in the Atlantic, NORPAX in the Pacific, and various individual research projects.

Several equatorial field programs are going on during 1979, the year of the First GARP Global Experiment (FGGE) (Figs. 4.1 and 4.2). In the Pacific Ocean, the main U.S. components are the NSF/ONR sponsored NORPAX program and NOAA's EPOCS program. These programs are designed to be complementary and to put together an ocean-wide view of the oceanic response to atmospheric disturbances during the FGGE year. The oceanographic program for FGGE was presented in a status report of the Scientific Committee on Ocean Research (SCOR, 1977). Figures 4.1 and 4.2 summarize plans for actual operations as of late 1978 (GARP, 1978b).

The study of equatorial processes in the 1980's will build on these beginnings. Long-term plans for such studies are laid out in differing detail in various plans: the NOAA Program Development Plan for EPOCS; the NORPAX Equatorial Plan; and the Recommendations for Ocean Research in the 1980's, from a series of workshops sponsored by NSF during 1977 on promising opportunities in large-scale oceanographic research (Center for Ocean Management Studies, 1977). A series of meetings on equatorial processes, including representatives from all the above groups, began in 1978 to lay out experimental plans for the 1980's and has laid the ground for such programs as Physics of the Equatorial Oceans (PEO) and Biology and Eastern Equatorial Dynamics (BEED).

Modeling of equatorial ocean processes. The oceanic processes in the equatorial region have received a great deal of attention from numerical and theoretical modelers in recent years. The basic dynamics of the observed fluctuations remain a major problem. Most of the models have started from the response of the equatorial ocean to changes in the trade winds.

Along the eastern equatorial Pacific these winds produce a cold water tongue which could cause cooling and atmospheric subsidence reinforcing the trade winds. This would be a positive feedback loop; whenever the trades falter this loop would reinforce the faltering tendency. For example, a period of strong trade winds should lead to an accumulation of warm water in the western Pacific. With a relaxation of the wind stress this warm water probably surges back eastward, reducing the atmospheric subsidence and further weakening the trade wind circulation. This feedback could be an important part of the El Niño phenomenon. The Pacific Ocean models describe the Kelvin, Rossby, and Yanai waves which develop from the change in surface stress and travel back and forth along the Pacific waveguide centered on the warm equatorial counter current and the cold undercurrent (Fig. 4.3). Results obtained with these models indicate current speeds and wave propagation rates both of the order of 0.5 m/s or more, resulting in local response times of up to half a year.

The tropical Indian Ocean differs from the Pacific in size and in having a solid western boundary and a fragmented eastern one, instead of the reverse. Another difference is that the surface stress changes here have a very pronounced monsoonal character (although a monsoonal effect is also observed in

Figure 4.1.--Projected locations of oceanographic programs during the first year of FGGE (GARP, 1978a).

Figure 4.2.--Projected locations of oceanographic programs during the second part of FGGE (GARP, 1978a).

Figure 4.3.--The equatorial current and wind systems.

the western Pacific). The models suggest that the principal oceanic phenomena of potential relevance to climate are the reversals of the western boundary current after the onset of the Indian Monsoon and the equatorially trapped waves. The rate at which the oceanic response propagates towards the west, the lag in the ocean response reversing the current, and the extent and structure of that current all are key parameters for testing the models.

Finally, for the tropical Atlantic Ocean the GARP Atlantic Tropical Experiment (GATE) has produced evidence of wave processes analogous to those postulated and observed in the other tropical oceans. The GATE data now being studied provide a new basis for modeling the equatorial upwelling and related phenomena along the African coast.

It is clear that simulation of the full complexity of the observed tropical circulation will require a stratified closed-basin model that employs the extratropical flow as a boundary condition. This requirement defines the most immediate modeling task for the equatorial part of the Ocean Climate Program. Beyond it lies the goal of a fully coupled ocean-atmosphere model which will include also the effects of the equatorial ocean anomalies on the global atmospheric circulation. However, at this stage the complete range of these effects remains to be clarified by the empirical studies proposed below as third equatorial component of the Ocean Climate Program.

Equatorial air-sea interaction and atmospheric circulation changes. This third component of the equatorial Ocean Climate Program will comprise a wide range of local process experiments and empirical studies of historical and continuing long-term observations of ocean and atmospheric parameters.

The core of such studies concerns tropical precipitation which releases latent heat, providing a large part of the total atmospheric heat intake. Precipitation also involves clouds, which are a critical factor in radiation, the main terrestrial heat balance item. The importance of other possible controls, such as the sensible and latent heat fluxes from the ocean surface, is more problematic, and these fluxes should be regarded as two-way interactions at this stage. Tropical rainfall certainly produces marked local decreases in both the air temperature and the salinity of the upper ocean, and these provide an alternative to the classical interpretation of the heavy Canton Island rains as due to unusually high ocean temperatures (cf. Fig. 2.3). Such circumstances dictate an open-minded research strategy that seeks an understanding of tropical precipitation from several directions.

The first objective must be to obtain representative estimates of rainfall amounts over the entire tropical area. Satellites make this an attainable goal; the development of an efficient remote-sensing rain estimating technique from various experimental satellite procedures will contribute very significantly to equatorial ocean climate studies.

Satellite cloudiness and radiation data that are used for such local rainfall estimates will also lead to a better understanding of equatorial mesoscale and synoptic-scale processes. Specific studies are needed of the location, structure, and behavior of the ITCZ and other forms of organized tropical convection and their interaction with the migratory weather systems of middle latitudes. Other studies should consider the planetary temperature contrast which controls the boundary between the trade wind circulation and the statistical westerlies produced by the baroclinically unstable disturbances of middle and higher latitudes. All these phenomena can be considered in terms of forcing by positive or negative SST anomalies in the equatorial zone. The associated ocean-atmosphere exchanges of heat, moisture, and momentum can be measured directly by aircraft with methods developed and tested in projects such as the IIOE, GATE, and NORPAX. Such measurements will also play an essential part in the conversion of satellite cloud drift winds to surface stress estimates, which in turn provide a crucial input for the modeling of SST anomaly development.

Sea surface temperatures also represent the main data set available for studies of longer-term ocean variability. Two separate lines of historical analysis can be followed. One emphasizes spatial continuity by using empirical orthogonal component representations of mean monthly SST anomalies and associated meteorological parameters. The other looks specifically for abrupt changes in the SST anomaly field and for associated changes in the behavior of individual synoptic systems. Both studies will be able to make use of long series of mean air temperature anomalies (mainly over the continents) and circulation type frequencies. In this way a coherent and complete empirical picture can be developed of climatic features associated with large SST anomalies especially in the equatorial Pacific. These results will serve also as a bridge from the tropical to extratropical parts of the Ocean Climate Program.

4.1.2. Heat Flux

Variability of subtropical gyres. The contribution of the oceans to the planetary meridional heat flux is largest in low latitudes. In fact, the oceans may be the main agents of heat transport up to a latitude of about 25°-30° (Fig. 2.5). Beyond that latitude, atmospheric processes clearly predominate. Within the subtropics, the flow of heat across any particular parallel circle appears to be governed mainly by the juxtaposition of a poleward flow of warm water, along the western ocean boundaries and in the surface layer below the trades, with a deep transport which moves colder water in the opposite direction. To a lesser degree, cold water also is transported towards the equator by localized quasi-stationary countercurrents and by currents along the eastern boundaries. Transient eddies seem to have comparatively little effect on the oceanic heat transport in the subtropics, particularly in the North Atlantic. There the Gulf Stream is constrained by the Straits of Florida, and the characteristic scale of the temperature field in its interior is relatively large compared to the length scale of the eddies. Eddy transports of heat become important in higher latitudes.

The effect of the subtropical gyre on the climate is particularly important in the North Atlantic where the gyre is the source region of the warm water which tempers the winter climate of western and northern Europe. It also has a large influence on the climate of the eastern North American seaboard. The sensitivity of these areas to climatic fluctuations is demonstrated by the fact that the large Pleistocene ice sheets all developed around the North Atlantic. Annual and interannual fluctuations of the oceanic heat transport are likely to affect the climate of the same areas on shorter time scales.

In the Southern Hemisphere the subtropics border directly on the unconfined southern ocean, a region of particularly intense air-sea interaction where warm waters from the north enter, undergo heat and salt transfers, and are recirculated into the subtropical gyres. In contrast to the Northern Hemisphere, where oceanic heat flux is small at high latitudes (Vonder Haar and Oort, 1973), the southern ocean seems to account for about one-third of the total poleward heat flux even at 60°S (Trenberth, 1979). Moreover, there is evidence that this transport undergoes large fluctuations on a time scale of several decades, (see Fig. 4.4b). These heat fluxes and the associated water mass production link the southern ocean with all the other major ocean basins, and understanding their fluctuations must form part of any attempt at understanding global climatic fluctuations.

To study the variability of the oceanic heat transport in the Northern Hemisphere, the first step is to learn how to monitor the North Atlantic heat transport across, for example, the 25th parallel over a period of at least several years. On the basis of the preceding considerations, it is believed that this can be done, to the first order, by measuring separately the contributions of the Gulf Stream in the Straits of Florida, on the one hand, and those of the deep and surface layer transports across the rest of the ocean, on the other hand. In the first instance, even monitoring of the Gulf Stream alone--though it would not yield absolute heat flux values--could greatly increase our knowledge about oceanic heat transport variability.

Figure 4.4.--Currents and climatic signals of the Southwest Pacific.

- a) Sea surface elevation above the 1000 decibar pressure level (~ 1 km depth), defining the surface (geostrophic) flow in the Antarctic Circumpolar Current (Gordon et al., 1978). The hatched area provided the climatic records in (b).
- b) Changes in the strength of the Southern Hemisphere (surface) westerlies and in sea surface temperature over the last century, aggregated for the 90° sector 150°W - 240°W and 40°S - 50°S . Note SST drop of about 4°C in 1870 and rise in 1917. Mean scalar wind is about 9 m/s. Note sudden drops about 1870, 1903, and 1917. A change from 12 m/s (+3) to 7 m/s (-2) corresponds to a change in wind stress of more than 300%. The related changes in ocean transport and dynamics are unknown. (Fletcher et al., 1979).

To study the variability of the southern ocean heat transfer and storage, the first steps must be to describe and understand low-frequency variations in the Antarctic circumpolar current, and to investigate the formation of water masses resulting from the intense air-sea interaction of the region, especially in the storms of the "roaring forties" and "furious fifties". This can be done initially by systematic meteorological, hydrographic, and current measurements in the region south of New Zealand (Fig. 4.4a) where the Antarctic Circumpolar Current (ACC) turns southward and intensifies at the Macquarie Ridge (160°E). A southern branch of the ACC continues zonally along the northern side of the Pacific Antarctic Ridge. A northern branch of the ACC moves along the southern flank of the Campbell Plateau; the 1.1 dynamic meter contour in Figure 4.4a indicates the approximate northern boundary of this current. Transport estimates suggest a baroclinic transport of roughly 60 million tons/sec for this northern branch. The dynamic contours indicate that the current follows the Campbell Plateau as far north as 50°S before heading zonally and eventually rejoining the southern branch.

The deep circulation in the South Pacific can be inferred from existing (admittedly sparse) hydrographic data. The western boundary for the deep South Pacific is New Zealand and the Tonga-Kermadec Ridge. The abyssal flow east of New Zealand is part of the Deep Western Boundary Current (DWBC). Waters in this current come from west of New Zealand. As these waters move circumpolarly some fraction leaves the northern flank of the Pacific-Antarctic Ridge, crosses the basin and piles up against the Campbell Plateau, the Bounty Platform, and the Chatham Rise to form the core of the DWBC. This current moves Antarctic bottom water northward into the subtropical gyre.

Together, the two regions (South Pacific and North Atlantic) here proposed for pilot studies of ocean heat flux and storage include the clearest examples of all the main mechanisms in question. Work in these regions is also convenient and cost-effective. The North Atlantic has already been studied more fully than any other ocean and is at the doorstep of several oceanographic institutions in the United States and other technologically advanced countries. The region south of New Zealand also has received considerable oceanographic and meteorological exploration in the International Southern Ocean Studies (ISOS) project; it contains the main access route to the American bases in Antarctica and to New Zealand and Australian stations on islands in the southern ocean. This makes it another promising area for international cooperation.

It must be stressed, however, that such pilot studies are merely one prelude to the ultimate requirement for monitoring the total poleward oceanic heat flux. Before that task can be tackled, other key regions should be investigated, such as the North Pacific gyre, and the area west of South America, where the Antarctic Circumpolar Current casts off the Peru Current and perhaps makes a broader contribution to the South Pacific gyre, before entering the Drake Passage.

The initial field study in the North Atlantic should include:

- Long-term frequency measurements of the velocity, temperature, and salinity structures of the Gulf Stream in the Florida Straits. The Gulf

Figure 4.5.--Circulation diagram for the total (top-to-bottom integrated) circulation in the North Atlantic (from Worthington, 1976, with permission of the publisher; copyright 1976 by the Johns Hopkins University Press). The straight lines have been added to indicate possible monitoring sections for a heat flux study. Contours are $10 \times 10^9 \text{ m}^3 \text{ s}^{-1}$ apart.

Stream is not only an important element in the meridional energy transport but also is an index of the momentum transfer from the atmosphere over the subtropical gyre to the ocean. Detailed measurements of the transports of mass and heat (defined in terms of some arbitrary reference temperature) by the Gulf Stream will be extremely valuable in testing theories of large-scale ocean-atmosphere interaction. In the Florida Straits the Gulf Stream is confined to a channel, so its transport is well-defined and can be directly measured.

- Repeated hydrographic measurements across the Atlantic along 24°N and 26°N . This data set, in conjunction with historical data, will indicate the mean temperature and salinity structure in this area. This can be used to test the present dynamical models of the interior of the subtropical gyre and to estimate the mean absolute flow integrated from top to bottom and the associated mean heat transport (see Fig. 4.5).

Figure 4.6.--Pilot study region southeast of New Zealand (Heath, Bryden, and Hayes, 1978).

The initial field study in the South Pacific should include:

- Ships-of-opportunity and aircraft XBT profiles, detailed hydrographic surveys, and velocity transects, to define appropriate spatial scales for moored arrays.
- Moored current meter, thermistor chain, and pressure gauge arrays. The deployment of an initial array can be based on the results of the ISOS pilot study of the area (Heath *et al.*, 1978; cf. Fig. 4.6). Another moored array of current meters and pressure gauges, supplemented by conductivity-temperature-depth (CTD) sampling would be used to study the interaction of the ACC with the Macquarie Ridge.
- Satellite tracking of drifting buoys and remote sensing of sea surface temperatures from satellites.

In addition to the field studies, a complementary program of empirical studies should be undertaken using existing oceanographic and meteorological

data and theoretical studies. These studies are essential if the experimental results are to be put in the proper historical context and tests of models are to be made. This implies considerable use of the data bases at the National Oceanic Data Center (NODC) and National Climatic Center (NCC).

Finally, greater emphasis should be placed on observational studies and modeling of the ocean-atmosphere boundary layer in tropical and subtropical regions. This boundary must be adequately modeled in the general circulation models because of important exchanges of heat, moisture, and momentum. Present formulations are based on representation of observations at middle and high latitude weather ships. More attention is needed to modeling the boundary processes in tropical latitudes.

Eddy transport of energy. Along the polar fringes of the great anti-cyclonic gyres, in the region of predominantly westerly winds, the surface layer and deep transports are thought to have the same direction. This would mean that the oceanic mass and heat transports have to be balanced partly by the eddies. Although they are not yet ripe for a major observational program, their role must be briefly considered here. Turbulent mixing by eddies is particularly effective in regions of relatively large horizontal temperature gradients. These usually can be found along the polar edge of the gyre. The thermal gradient across the western boundary currents also increases with increasing latitude. The associated increase in eddy activity is particularly pronounced in the North Atlantic where the Gulf Stream escapes the confining limits of the Florida Straits as it enters temperate latitudes, as well as in the vicinity of the Antarctic Circumpolar Current.

Eddies can affect the transport of heat by the western boundary current both by lateral mixing and by driving rectified flows. For example, one or two standing eddies which accompany the Gulf Stream on its offshore side effectively reduce the heat which is advected northward. Because the thermocline is deeper on the offshore side of the stream, warm water is advected towards the Equator by the eddy-driven counterflow in this area. Changes in this recirculation may have major effects on the integral heat flux. By contrast, the mass transport of the stream tends to be increased by the recirculating water.

The intensity of both the standing and the transient eddies will be affected by the baroclinicity in the area of their development. The baroclinicity is governed, in turn, by the mass structure--that is, by both the temperature and salinity profiles--of the water which flows northward in the stream. Finally, this mass structure and the associated available potential energy can be related to the energy input across the interface in the interior of the subtropics.

Modeling studies of this chain of processes have now been started. Observational studies would best be carried out as contributions to the Polygon Mid-Ocean Dynamics Experiment (POLYMODE) which is concerned with some of the relevant problems. Continuing monitoring of the POLYMODE region and surface monitoring from satellites might be considered future possibilities.

4.1.3. Storm Transfers

The motivation for a Storm Transfer and Response Experiment (STREX) comes from the observed relationship between cyclogenesis and storm movement on the one hand and the ocean temperature distribution on the other. We know enough about boundary layer processes to recognize that storms probably contribute in a highly nonlinear fashion to surface momentum flux, heat and vapor transfer, and precipitation. In view of the fact that storms at any one time occupy something like one-half of the ocean surface in middle and high latitudes, understanding of their boundary-layer processes is important to a number of interrelated scientific objectives: weather prediction; seasonal, internal and longer changes of climate; the global hydrologic cycle; generation of surface and internal waves; dynamics of upwelling; and ocean currents.

Storm boundary layers exhibit a variety of mesoscale phenomena which are undoubtedly associated with characteristic secondary flows. In areas of large-scale divergence in the western portion of storms, cellular stratocumulus clouds are often observed in the layer under the marine inversion. In other areas, clouds appear in parallel bands. Thus, the character of mesoscale convection and convergence appears to be subtly different in different regions of a particular storm, but the relationships to air-sea temperature difference, windspeed, or other aspects of the boundary layer are not understood. In areas of large-scale convergence and deep atmospheric convection, convergence and precipitation are highly concentrated in mesoscale bands. It is not clear whether any of these structures, either in areas of large-scale divergence or convergence, play an important role in altering their larger scale environment. It has been suggested, however, that these characteristic patterns of convergence and precipitation represent an atmospheric adjustment tending to maximize heat flux and energy generation.

An active and important debate concerns whether large scale ocean surface temperature anomalies influence subsequent large scale atmospheric circulations or whether these anomalies result from atmospheric circulation changes. In either case the discovery that the magnitude of seasonal anomalies is simply related to the date of transition of the ocean mixed layer from winter to summer regimes by storm mixing reveals a specific linkage of the atmosphere and ocean and suggests a possible mechanism of ocean influence on atmospheric circulation on an extended time scale. STREX will contribute to understanding of these relationships and the responsible mechanisms.

The upper ocean accepts the fluxes at the surface and transfers them horizontally and downward by a number of processes. Among these are local shear, internal waves, inertial oscillations, Langmuir circulations (Assaf et al., 1971), and small-scale turbulence. The storms of interest in STREX perform work on the ocean and increase the local potential energy of its surface layer. How is the work done, and how is the energy dissipated? The answers lie in the knowledge of the turbulent scales during strong mixing events. The mature storms produce the strong events, but neither theory nor experiment has yet addressed the relevant parameter range. For example, what role do internal waves play in the relaxation of the ocean after storms? Is the surface layer a significant region for generating internal waves? Do the inhomogeneous stresses at the surface drive secondary flows, or create local shear for mixing?

The energetic scales of turbulent eddies, and their transfer during the wind-mixing of momentum, heat, and salt are crucial to the upper layer structure; so is the turbulent dissipation of the finer scales. Results of experiments in weak storms like the Mixed-Layer Experiments (MILE) will be required before such measurements under mature storms are possible. The microstructure measurements in MILE will allow estimates of the turbulent dissipation to be made, and should yield methods of parameterization that dissipation.

A second point is the response of the ocean on the atmospheric space scales. What are the magnitude of convergence and divergence on these large scales, and how can they be correctly mapped? How typical are point measurements? Studies of representativeness will be required before a larger-scale study like STREX can be carried out. Such studies include both MILE and the Joint Air-Sea Interaction Experiment (JASIN).

The STREX research plan calls for observing boundary layer processes in the vicinity of Ocean Station PAPA during passage of about 10 storms. Figure 4.7 shows schematically the sea level pressure pattern of typical Pacific storms and the motion of Ocean Station PAPA relative to ten storm tracks. Composited time series of significant features and processes during such passages will supplement and modify in major ways the current views on the structure of storms; they will also contribute to the development of better numerical prediction models, and to the understanding of ocean atmosphere interaction on time and space scales from the mesoscale to the synoptic scale.

Plans for STREX have been developed through collaboration of scientists from several agencies and institutions. Planning conferences in 1977 and 1978 have developed the scientific objectives and general plan, and a conference at GFDL May 24-26, 1979, focused on data and facility needs. A schematic experimental plan is shown in Figures 4.8 and 4.9. Figure 4.8 gives the region of the Pacific to be covered by the experiment, while Figure 4.9 shows alternate flight plans for aircraft expendable bathythermograph (AXBT) deployment on flights from Kodiak. The first field observations have been scheduled for the fall of 1980 prior to the expected termination of regular observations at Ocean Station PAPA. The program depends heavily on satellite data and calls for use of the Canadian weather ship, a NOAA oceanographic ship, several aircraft, and anchored and drifting buoys. The Institute of Ocean Sciences and the Atmospheric Environment Service of Environment Canada are planning vital parts of the STREX program.

4.1.4. Ice-Ocean Interactions

One of the strongest annual signals in air-sea interaction is the variation of sea ice extent and concentration. These features determine the albedo of the polar regions and are determining factors in heating patterns and upper-ocean mixing parameters (wind stress, salt sources and sinks, and stratification). The mean amplitude of this signal is particularly large in the southern ocean, but year-to-year variations appear to be large in both hemispheres. Considering that only a small perturbation in the meridional transport of heat in the upper ocean is needed to either induce or prevent the formation of ice on water that is close to its freezing point, it is not surprising that modelers are just beginning to learn how to simulate the mean

Figure 4.7.--Schematic diagram illustrating the motion of Ocean Station PAPA (dashed lines) relative to the typical sea level pressure distribution (solid lines) for ten hypothetical storms.

annual variations of sea ice (Parkinson and Washington, 1979). This ability is important, especially in view of the much quoted but not fully proven suspicion that the cryosphere can interact with the ocean and the atmosphere in a positive feedback mode. For example, anomalies of ice extent and temperature over the whole ice pack region could be positively correlated. Air-sea interaction over that region, and especially in the coastal belt where katabatic winds blow the ice away from the Antarctic continent, clearly is a primary source of both sea ice and deep cold waters of the ocean.

Figure 4.8.--Location of storm transfer experiments.

The meridional transport of heat in the subpolar oceans is one of the controlling factors for sea ice. We consider the two polar regions separately. In the Arctic, the modeling of the ice pack shows that the extent of ice is sensitive to the amount of heat advected by the ocean. The primary source of this heat is the flow between Greenland and Spitsbergen, the only deep passage into the Arctic Basin. Preliminary studies have shown that the necessary technology exists for long-term measurements of currents and temperatures in this passage, and that the heat inflow is relatively large. This is a good region for such measurements because the net mass flux is small. A program to measure the heat transported by the ocean and by the ice in this region has been proposed as part of the Polar Sub-Program of GARP, and studies will continue through FGGE. Specific contributions to this study include satellite monitoring of the position of the ice edge, and monitoring of the amount of ice advected out of the Arctic basin. Such work is now supported by NOAA, NASA, NSF, and ONR.

In the Antarctic, meridional transport may be important to all longitudes. The large extent of the ocean area around the continent, and the fact that we know so little about where the heat is actually transferred, means that experiments to study the large-scale heat transport will have to wait until remote sensing techniques are further refined. However, specific point

Figure 4.9.--Alternate flight plans for AXBT deployment on flight from Kodiak. Insert shows deployment in vicinity of Station P (designated by number 5).

studies already are underway and the NOAA capability for collecting and archiving data on the hemispheric extent and concentration of sea ice creates a basis for a full program including empirical studies of historical and present satellite data and modeling. Satellite monitoring of sea ice extent in the Southern Hemisphere seems especially promising in view of the evidence presented by Budd (1975) that the ice has a stable feedback relationship with the annual mean temperature along the Antarctic coast. Any CO₂-induced temperature increase could then be revealed first by a systematic reduction in the Antarctic sea ice extent.

4.1.5. Geochemical Exchanges

The 1977 NSF/IDOE workshops on ocean research in the 80's considered the question of the role of chemical oceanography in climate studies. The report from the workshops (Center for Ocean Management Studies, 1977) pointed out that:

Exchanges of gases between ocean and atmosphere have a profound effect on climate. One example is the increased atmospheric CO_2 concentrations coming from burning fossil fuels which cause warmer surface temperatures, resulting in shifts in distribution of crops and their yields. Yet some fraction of this CO_2 goes into the ocean and its sediments, thereby reducing possible temperature changes caused by CO_2 buildup in the atmosphere. Thus, an understanding of the buildup of CO_2 in the ocean and the atmosphere may provide the basis for more accurate climatic predictions.

The report goes on to ask: what are the fluxes of climatically significant gases between the atmosphere and the surface ocean? It continues:

The atmosphere is a critical transport path, involved in the environmental cycles of a wide variety of natural and anthropogenic substances. At present there is considerable uncertainty about the atmospheric sources, sinks, and cycles of several trace gases including CO_2 , N_2P , and the fluorocarbons which may affect the ozone layer and climate. Our understanding of the role of the ocean in the atmospheric cycle of these substances is still poor. There is evidence that the geochemical cycles of other substances such as sulfur compounds, CO , NO , NO_2 , NH_3 , CH_3 , PCB, DDT, CH_4 and other organic materials, involve significant air-sea exchange components, but very little is known about the magnitude, or sometimes even the direction of the flux....

In order to understand fluxes of certain inorganic substances we need to know the flux of organic material from terrestrial sources to the ocean, how much marine-produced material is transported across the air-sea interface into the atmosphere, and for which organic compounds these processes are important. We have now arrived at a stage with organic analytical techniques that we can separate and identify very small amounts of material. Initial studies, although scattered, show the potential of using organic compounds as tracers for specific sources, either certain species of land plants or marine bacteria....

The sea can be both a source and sink for many substances in the atmosphere. It will be important to distinguish between recycled materials from the ocean and a true net input to the ocean. This can be facilitated by the use of certain tracers which are non-marine in origin, such as P_b and possible certain organic compounds, and by a better understanding of the reinjection mechanisms....

The fate of the atmospherically deposited material in the ocean must be determined. Material on the deposited particles may be rapidly solubilized and made readily available for biological uptake....

Atmospheric inputs to the open ocean arise from both gaseous and particle transport mechanisms. Compared to many of the fluxes we seek to determine, those of gases between sea and air have been reasonably well established. Nevertheless, there are important aspects of this problem yet to be studied:

- The dependence of exchange rate on the molecular diffusivity of the particular gas needs to be established in order to use the results for selected tracer gases (Rn-222, $^{14}\text{CO}_2$, or He-3) to determine rates for other gases of interest (O_2 , CO_2 , CO, N_2O , He, Ar...). To determine these exchange rates, multiple tracer experiments must be carried out in enclosures, lakes and wind tunnels.
- The wind velocity dependence of gas exchange has not yet been established in the field. Data on Rn-222 suggests that the rates are not proportional to the square of the wind velocity. To pin this down, time series of radon must be run at single oceanic localities such as areas with shallow (20-50 meters) mixed layers, which are subject to frequent passage of storms.
- It has been suggested that hydration of CO_2 to H_2CO_3 is catalytically enhanced in seawater compared to pure water. This would increase the rate at which CO_2 gas would exchange with the HCO_3^- in seawater. However, others have postulated that enhancement does not occur. Yet measurements of bomb C-14 yield a higher mean exchange rate than those of Rn-222. Experiments should be carried out to determine if such catalysis really occurs. There is today considerable uncertainty as to the global fate of certain gases which are being produced at increasing rates as a result of human activities: two such examples are CO_2 and N_2O . With regard to N_2O , the evidence is inadequate to decide whether the sea serves as a sink or source for this gas.

Chemical oceanographers are now planning a number of studies to address these problems. One of these studies, "Transient Tracers in the Ocean," will utilize natural and man-made oceanic tracer transients (e.g., radiocarbon, tritium) to study residence times, transport mechanics, and vertical mixing. More generally these atmospheric aspects and transfer processes form the subject of a parallel program plan concerned with variations in atmospheric composition and solar radiation as factors in climate.

This concludes the program outline for the process and regional experiments concerning ocean climate. A summary is given in Table 4.1.

Table 4.1.--Participants and time schedule for process/regional experiments

Physical Process	Time Schedule	Interested Organizations
Equatorial Dynamics	Begin during FGGE. Major programs through the 1980's.	NSF, NOAA, ONR, NASA. Major oceanographic institutions.
Heat Flux	Pilot studies begin in 1980. Long-term observations after 1985	NOAA, NASA, NSF.
Storm Transfer	First experiment in 1980, second in 1981. Further experiments only if required.	NSF, NOAA, ONR, NASA.
Ocean-Ice Interaction	Polar sub-program of GARP begins in 1977. Observations throughout 1980's as part of World Climate Program.	NSF, ONR, NOAA, NASA.
Geochemical Exchanges	Surveys of transient tracers begin in early 1980's. Chemical process studies now underway.	NSF, ONR, NOAA.

4.2 Ocean Observations

According to GARP (1975) the nature of the climate problem makes it certain that a major ocean observing system must be eventually devised and established. Moreover, our empirical knowledge of the ocean is very incomplete, especially as regards variability. With the exception of some coastal stations, long-time series of measurements of oceanic variables are virtually non-existent. Thus one priority is to start now with a long-term commitment to direct observations in a relatively few regions, to be chosen on the basis of the best estimate of their dynamical importance. Another is increasing use and critical appraisal of ocean parameters which can be measured (at least in principle) remotely from space.

In terms of prediction, we know that updated data about the present climate must be continually introduced into a realistic coupled atmosphere-ocean model in order to compute the future climate and to verify the predictions made in the recent past. It is not certain whether ocean surface data alone will be sufficiently representative for such a coupled climate model. Our uncertainties of the actual nature of the ocean-atmosphere interaction make it difficult to determine how far below the surface we must go in our observational program and what variables should be measured. Uncertainties also exist about the best horizontal distribution of such measurements and the frequency of sampling.

Table 4.2.--Priority systems for observation of ocean climate

Type of System	Advantages
Ships of opportunity (NSF, NOAA, ONR)	regular networks low cost coverage of large areas
Phantom weather stations (NOAA)	fixed point data collection network up to 100 possible stations low cost
Island stations (NSF, NOAA)	proven utility reliable, unattended instrumen- tation available low cost for long-term records
Moored arrays (NOAA)	provide long-term records of current temperature used together with hydrography, yield variability of circulation
Repeated hydrographic sections (NOAA)	observations of gyre variability observations of water mass formation

Therefore, it is essential that we begin immediately to make observations of a few variables in a few locations. The results can be used for various empirical data correlation studies and to establish the importance of the various station. These initial data can then be used, together with the data from the various process experiments, to determine the next step towards a global ocean observing system.

The National Academy of Sciences report on "The Ocean's Role in Climate Prediction" (National Academy of Sciences, 1974) noted that the 18°C water in the subtropical northwest Atlantic serves as a horizontal homogenizing pool for horizontal scales of long-term changes. However, the indices of long-term variations in the Gulf Stream have not been identified in the same way as have changes in the Kuroshio-Oyashio front. The greatest need in the Atlantic analysis of temperature is for placing the results in relation to those for the other oceans, while the greatest need in the Pacific is for extending the length of the data series by continued observations. Salinity time series are valuable in the Pacific, since they appear to be especially sensitive to interannual variations there.

We list below four types of observing systems which could be implemented to cover the processes mentioned above. These are summarized in Table 4.2. Some of the systems listed also provide ground truths for satellite measurements which may be destined to provide many of the global monitoring needs of ocean climate in the long run.

Ships of opportunity and phantom weather stations. Ships of opportunity are merchant ships that make routine observations along regular routes. They constitute a regular network of repeated sections and provide coverage of large areas at relatively low cost. The disadvantages are that data are concentrated along the main shipping routes, and large areas are left without cover. The NORPAX program has made good use of such data for the Equatorial and North Pacific.

The phantom weather station concept also depends on the use of commercial ships for data collection. Several routes worked by the major fleets cross hydrographically critical and representative sites. If observations could be made at each crossing, we could approach a fixed point data collection network for these sites. In this concept, the major carriers would be responsible for one or two stations which they alone would occupy and which would be located at the most favored location along their most traveled route. The existing network of routes suggests that up to 100 such stations could be established.

Island stations. Tide gauge records and sea level records from coastal stations and islands have proved enormously important in establishing empirical air/sea interactions and telecommunications. These records represent some of the longest data series we have. It is essential that the current records be maintained. Furthermore, the addition of sea level measurements to all islands in representative mid-ocean areas is probably the most cost-effective next step that could be taken towards a global ocean observing system. The technology for reliable automatic surface weather measurements with satellite readout is near, and all representative island stations should be equipped with sea level gauges and automatic weather stations with satellite readout.

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

Repeated hydrographic sections. Recent work is beginning to show that sufficiently detailed hydrographic data, with a few direct current observations, may be sufficient to establish the ocean circulation variability. In order to tell whether this is true, a series of repeated hydrographic sections across selected areas of the ocean are required. For example, a section could be run from Woods Hole to Bermuda and from Bermuda to Miami, to establish the variability of the hydrographic field over a period of several years. This work would be an integral part of the pilot studies of meridional heat flux (Section 4.1.2). Such a program would need to start with a minimum of three to four sections more per year; more might be needed to offset the effects of eddies. The analysis of the data would then indicate how often the section needed to be repeated.

It seems logical for NOAA to operate a number of these observing programs. For example, the sea level stations and ships-of-opportunity program now being run by scientists in NORPAX could be a long-term operation of NOAA's National Ocean Survey. A centralized management of the climate program could help to take advantage of these opportunities.

Measurement techniques must be perfected at the same time that the above experimental observations are taking place. A series of studies aimed at producing efficient and cost-effective techniques for long-term measurements in the ocean is needed, since long term measurements are central to the climate problem. Instruments of maximum interest and usefulness to the climate studies currently underway should be developed, and these instruments should be tested in the studies. Five major systems deserve study:

- Deep pressure gauges. A considerable effort has gone into making a reliable deep-sea pressure gauge as part of the warning system for tsunamis. The techniques developed would be used to produce a long-term deep-sea pressure and temperature measuring system with remote data recall and to adapt a shallow system for satellite data transmission.
- Bottom-mounted electric field recorders. These devices yield measurements of the vertically and horizontally averaged transport of water in the deep sea. Existing systems and modifications for long-term deep-sea use would be tested, and the output data would be compared with those from direct current measuring systems in the equatorial and heat flux experiments.
- Drifting buoys. Work is needed on interpreting drifting buoy measurements and measurements with existing systems in the equatorial and heat flux experiments. The synoptic view obtainable from a field of many drifters with satellite readout could provide major advances in our understanding of the large-scale surface circulation and heat storage.
- Acoustic current measurements. Studies of techniques for measuring averaged currents by acoustic travel time and Doppler shift are needed. These techniques will allow measurements of currents at any level.
- Surface layer variables by remote sensing. Remote techniques developed in NOAA promise measurements of temperature and salinity to depths as great as 100 meters. If such techniques prove reliable, the whole concept of monitoring surface layer heat and salinity storage could be radically changed. These techniques should be tested in the context of oceanographic experiments such as the equatorial dynamics and heat flux studies.

In terms of remote sensing from space, a detailed analysis of measuring ocean parameters has been presented in NASA's "Proposed Contribution to the Climate Program" (NASA, 1977). That report emphasizes the need for advanced instrument development on sea surface temperature measurements and sea surface

elevation relative to the geoid. Sea surface elevation measurements would provide a synoptic view of ocean surface currents and therefore deserve high priority. Remote measurements of wind stress (momentum flux), fluxes of sensible and latent heat, and radiation need extensive in-situ truth, and therefore special studies on these fluxes are planned by NASA during the next five years.

5. A POSSIBLE ORGANIZATION FRAMEWORK

5.1 National Coordination and Planning

No one agency possesses all the resources and expertise needed for the ocean climate program. All of its studies require contributions and support from government agencies, universities and oceanographic institutions. In order for the program to be successful, close coordination of all of these studies is necessary.

A possible coordinating mechanism is schematically indicated in Figure 5.1. Under this mechanism, general oversight of national ocean climate studies would be vested in an Ocean Climate Council operating under the aegis of

Figure 5.1.--Coordinating mechanism for the ocean climate program.

the United States Climate Program Office. The Council would be made up of representatives of the various agencies and programs that constitute the Ocean Climate Program.

The Council would provide recommendations on agency emphasis of different programs, make budgetary reviews and comments for the entire program, and organize annual meetings, newsletters, and reprint volumes as appropriate. The most important task of such a Council, however, would be the overall coordination of a program with many diverse parts. Such coordination is lacking now and is essential for an optimum Ocean Climate Program, especially in joint interagency planning.

Under this plan, the Council would be able to turn for advice and direction as needed to a Panel on Ocean Climate which could be part of the Climate Board of the National Academy of Sciences. Alternatively, the Council could use the existing Panels and Committees of the Academy.

5.2 International Coordination and Liaison

Plans are being developed for the World Climate Program, under the sponsorship of the World Meteorological Organization. Such a program is expected to include the next phase of the Global Atmospheric Research Program as it moves into climate research. A Committee on Climatic Changes in the Ocean is being established to provide liaison between the Scientific Committee on Oceanic Research (SCOR) and the developing international climate programs.

The United States contacts with the international climate programs will be through the U.S. Climate Program Office. It is expected that the Ocean Climate Council would provide liaison between the various SCOR working groups on climate-related topics and the relevant national programs, by working through the U.S. Climate Program Office (Fig. 5.2).

The initial international framework is that of the First GARP Global Experiment (FGGE) of 1979. FGGE is the first opportunity for oceanographers to carry out ocean-wide studies in the context of a global meteorological experiment. The scientific understanding and management techniques learned during the FGGE will help substantially in the establishment of an ocean climate program for the 80's, as outlined in this report.

Figure 5.2.--International coordination and liaison.

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