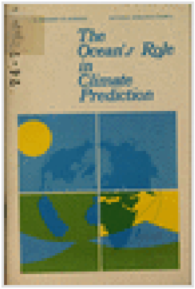

Role of the Ocean in Predicting Climate: A Report of Workshops Conducted by Study Panel on Ocean Atmosphere Interaction Under the Auspices of the Ocean Science Committee of the Ocean Affairs Board, Commission on Natural Resources, National Research Council (1974)

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National Academy of Sciences
Washington, D.C. 1974

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The members of the committee selected to undertake this project and prepare this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. Responsibility for the detailed aspects of this report rests with that committee.

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FOREWORD

More than a year has elapsed since the close of the two workshops that generated this report. During that time the idea that the ocean plays an important role in climate prediction, and that there are practical, rational means by which we can attempt to develop a more precise predictive ability, received national recognition.

As the sense of urgency deepened, government scientist began formulating a National Climate Plan. An ocean monitoring scheme is now being proposed as part of that Plan. There is therefore some indication that a global monitoring system may come into existence sooner than we had expected, and that it may place heavier emphasis upon moored instrumentation than we had judged feasible. On the whole, we agree that acceleration of climate prediction is a step in the right direction, and that if national priorities demand it, some things may be done in parallel that otherwise might have been done consecutively. What we hope our report successfully conveys is the idea that achieving a climate predictive ability is going to be a complex enterprise with many difficult tasks, of which designing a monitoring system is only one.

Henry Stommel
December 1974

PREFACE

In recent years, meteorological scientists have succeeded in producing increasingly sophisticated numerical models of the atmosphere that simulate more realistically the weather and climate of the world. Now they are pressing, through international organizations, such as the World Meteorological Organization in Geneva, to improve the global measurement system that is fundamental to accurate predictive capability. Their Global Atmospheric Research Program (GARP) has two objectives: to increase the accuracy of forecasting the weather over periods from one day to several weeks and to understand the physical basis of climate. There is little need to emphasize the economic and environmental benefits that would accrue from such an improvement in predicting weather and climate.

It has become generally recognized that some of the activities of an industrial civilization such as we now enjoy may produce unexpected alterations in the climate of the earth. Our ability to regulate our industrial activity to protect, or possibly to improve, our world climate must depend on our scientific understanding of the physical processes that determine climate as well as our ability to measure and monitor those properties of the envirnoment that affect the grand machinery of climate.

The role that the ocean plays in effecting climate interests a large number of scientists with diverse interests and backgrounds. Recognizing the need to focus on this subject, the Ocean Science Committee of the Ocean Affairs Board appointed an *ad hoc* steering committee to organize a workshop to examine the scientific problems of large-scale ocean-atmosphere coupling (particularly as they relate to the ocean's effect on climate). To produce conducive conditions for in-depth discussion and an exchange of ideas and plans, the Steering Committee organized a two-part workshop corresponding to the pattern of scientific activity involved.

Accordingly, the first session of the workshop was built around activities which involve oceanographers who are designing and carrying out expedition-type experiments at sea. Oceanographers have already recognized that many important oceanic problems are so big and difficult that they must combine their resources to effectively attack them. Therefore, we are beginning to see spontaneous and fluid groupings of oceanographers whose aim is to grapple with certain long-period, large-scale phenomena in the ocean. Among these it is possible to identify nine groups that are planning work on different open ocean experiments. By discussion among oceanographers from these groups during the first session, it was hoped that we could identify possible areas of cooperation in the field work and that we could help the project planners to clarify their own ideas. It should be emphasized that these are all open ocean experiments which the scientists involved expect to carry out themselves.

By way of contrast, there are other areas of investigation in the phenomena of long-period large-scale variability of the ocean which depend on large volumes of data garhered in routine fashion by governmental agencies: for example, sea-surface temperature data that come in through the world weather reporting network of the World Meteorological Organization, various fisheries agencies, etc.; or, as another example, regular tide and sea-level data. Scientists who are interested in the analysis of these data and in suggesting ways in which these data can be augmented in quantity and quality as well as identifying new kinds of data obtainable by remote sensing techniques, are faced with rather different types of problems than those who are planning individual field experiments. Therefore, Workshop Session II was held to assemble those oceanographers interested in the studies of these source climatological data. The ideas considered during the second session need to be closely coupled with the planning of meteorologists for the First Global GARP (Global Atmospheric Research Program) Experiment (FGGE), because in most cases the needs of oceanographers and meteorologists will often be met by instrumentation on the same vehicles, free-floating instruments, and moorings.

This report is intended:

1. To provide an overview of the present and projected large projects currently related to the second GARP objective to understand the role of ocean in climate;

2. To formulate specific questions that appear to be vital to our understanding of the role of the ocean in the climate;

3. To report on the activities that are actually taking place and to assess how they stand in regard to the total task that needs to be done; and,

4. To indicate where the First GARP Global Experiment (FGGE) provides opportunities toward understanding the ocean-atmosphere climate problem.

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CHAPTER 1

A CLIMATE-PREDICTING SYSTEM

In the future it seems certain that there will be large numerical models that describe and predict the evolving climate of the earth; and that these models will include atmospheric and oceanic parts. As an exercise, we will consider the feasibility of constructing such a model, including what elements it must contain, and assessing what will be required from oceanographers to make progress toward building their oceanic part of the model. It is still quite uncertain what processes this model must include. Some essential ingredients will be: the surface mixed layer in the interior of the ocean; regions of great heat transport such as the Gulf Stream and Kuroshio; processes of vertical heat and water flux across the ocean surface; and sea ice. However, it is less certain whether the deep ocean circulation must be included. It is also uncertain what range of frequencies and scales must be reproduced and predictable in the ocean model so that it may interact properly with the atmospheric model to reproduce and predict climatic variation.

Figure 1 illustrates, in a greatly simplified schematic form, the nature of the climate model and how the two parts are connected. The vertical arrows indicate the ocean atmosphere interactions.

For the last 20 years, meteorologists have constructed numerical models of the atmosphere capable of predicting weather up to 5 days. A theoretical limitation of the short-term predictability of the atmosphere appears to limit useful forecasts to periods shorter than 2 weeks. Expressed somewhat differently, it appears that the atmosphere resembles a first-order Markov process with a memory of about 5 days. In short, the extreme nonlin-

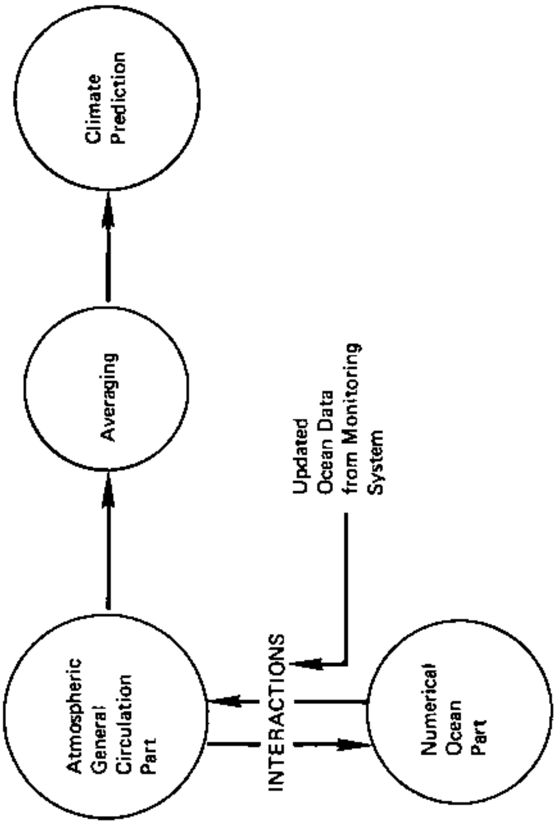

FIGURE 1.   Schematic numerical climate model

earity of hydrodynamical equations and the economic limits of conceivable observationsl programs make detailed weather forecasts beyond this period of time extremely difficult.

Climate, a statistical description of the state of the atmosphere, describes an average over many short-period weather disturbances. So defined, climate does not remain constant forever. Indeed, everyone is familiar with the idea of very long-term fluctuations in climate, such as ice ages. There are even very definite climatic differences over periods of a month or a season, or between 5 and 10 years, that stand out statistically above the noise level that is expected to be produced by the strongly fluctuating synoptic disturbances. Thus, we can speak meaningfully of warm years and cold years and of decades of anomalous pressure patterns over the whole northern hemisphere.

Such climatic fluctuations are very important to fisheries, transportation, industrial operations, and agriculture. They determine whether a country will have a good wheat crop, whether there will be famine in India or Africa or a widespread failure of the fisheries off Peru or of the rice crop in Japan, and whether this will be a bad year for ski resort operators. Such climatic fluctuations, which exist in bewildering variety, have directly influenced the rise and decline of civilizations and thus are one of the main influences on the history of mankind. We would hope to reproduce such climatic fluctuations in our hypothetical coupled atmosphere-ocean numerical model. Although we can not expect to predict the time and arrival of an individual cold front or hurricane twenty years from now, we hope that we will be able to predict in some average form such statistical information as changes in the average intensity of cold fronts or probability of hurricanes over periods of several months or years.

One of the main reasons we think that this is feasible is that, although the atmosphere itself has a very short "memory" (a few days), the ocean thermodynamically has a much longer one (a few months). The ocean, which has a larger heat capacity than air, can store vast amounts of heat with small changes of temperature below the surface of the sea. It can then give the heat slowly back to the atmosphere over long periods of time. Also, the memory of snow and ice cover accumulating on the surface of the land and sea has a very profound effect on the radiation balance of the earth. Thus the ocean, as well as the snow and ice cover, is an important component of any future numerical model for long-term climatic prediction. Our information about variability of heat storage in the ocean extends from single-day observations of heating in the shallow surface layer to inferences about temperature change over millennia based on paleontological information from ocean sediments. Because of this very wide time-spectrum involving a great diversity of processes and geographical locale, our information on past ocean occurrences is incomplete. In addition, our knowledge of the physical mechanisms underlying the changes in the ocean and of how these changes are quantitatively related to corresponding changes in the atmosphere is very meager.

Now we will consider how to construct this coupled atmospheric-oceanic numerical climate model. With present atmospheric models an enormous amount of numerical detail must be computed in the form of weather systems that probably bear no reality in detail, but which are necessary to compute in order that they may be averaged over to make the climate prediction. Computing all this false weather in detail is very uneconomical and may be misleading. In the future, we hope to discover means of computing statistical climatic averages directly without involving the long and detailed calculations of individual weather systems.

In the ocean part of the model, it is still quite uncertain what computations will be required, and only with further endeavors can we decide what the proper model will be. To develop a proper oceanic model, four avenues of scientific activity must be investigated simultaneously.

1. Descriptive and Statistical Analysis of Past Climatic Oceanic Data. This activity includes study of such sources of data as the 48 million surface observations obtained over the last 100 years by merchant ships in the world oceans and extracted from their logs. It also includes sea level observed by tide gauges, special historical programs of observations that have been maintained for as much as 70 years by such organizations as national fisheries services, and during the past 30 years, ocean "weather" ship data.

It is somewhat ironical that in this period of concern about monitoring the environment that these weather ships are being withdrawn from the ocean and that no substitutes have been proposed. Although we recognize that these so-called "weather ships" were actually stations established primarily for aircraft navigation and safety, they, nonetheless, have served as valuable platforms for collecting meteorological and oceanographic observations. For example, Namias and Bjerknes extracted from these sources of data important information relating to the existence and nature of long-term anomalies of sea-surface temperature in the Pacific Ocean. Parallel studies of oceanic data have also been made in the Atlantic.

From the days of Helland-Hansen and Nansen to the more recent investigations of Rodewald and Dickson, it appears that there are identifiable and distinct regimes of sea-surface temperature anomaly and of meteorological circulation anomalies with periods from 4 to 10 years. Modern computing machines make it possible to contemplate more elaborate statistical studies of the existing bodies of data. It seems likely, however, that this more or less randomly taken data, collected by merchant and naval vessels, will not be adequate for the use of oceanographers and meteorologists in running their future ocean atmosphere climatic model.

2. A Globally Planned Monitoring System. Updated data about the present climate must be introduced into a realistic climate model in order to compute the future climate and to verify the predictions made in the recent past. As a second activity, it seems likely that there will also be a globally planned monitoring system. This system will include the present sources of data from merchant ships and tide gauges, as well as other sources of data such as from geostationary and polar orbiting satellites. It is not certain, however, whether surface data alone will be sufficient to update the joint numerical climatic model. Perhaps special installations like moored or drifting buoys will prove capable of telemetering data on the subsurface structure in the ocean. Again, our uncertainties of the actual nature of the ocean-atmosphere interaction makes it difficult for us to determine how far below the surface we must go in our monitoring program and what variables (temperature, velocity, pressure) must be measured. Uncertainty about

the horizontal scales also must be resolved in this monitoring scheme of the future. In addition, we wonder how frequently the observations must be obtained in order to give an adequate monitoring system for updating the joint ocean-atmosphere model.

Development of an ocean monitoring system can begin with the testing and inventing of different schemes for monitoring ocean variables. Programs of buoy and sensor development and trials of various methods of telemetering data need to be encouraged. Despite all these labors, a monitoring system cannot spring fully developed as a final and complete design until a third avenue of activity is simultaneously pursued.

3. Process-Oriented Experiments. Special process-oriented field programs are required to gain the understanding necessary to parameterize particular processes into large-scale models. For example, scientists must make detailed studies of particular thermal anomalies in the ocean to discover how they are formed, how heat is transferred vertically in the ocean, how it is released, under what circumstances it becomes available to the atmosphere, and whether surface thermal anomalies are purely local phenomena that can be explained without a theory of the general ocean circulation or whether they are, in some important way, carried about by ocean currents so that it will be necessary to also predict the fluctuations of the more general currents. Process-oriented field programs must therefore be designed and executed to understand the nature of thermal anomalies, of the physics of the general circulation (including mesoscale eddies) of the open ocean, of the special processes which operate along coasts (such as upwelling phenomena), of transient, forced current systems such as those associated with such major atmospheric forcing as the monsoons, and of the distribution of geochemical tracers that has resulted from centuries of slow deep-water flow and diffusion.

4. Numerical Modeling. Numerical models of climate, obviously dependent on the third avenue of activities; need to incorporate all the necessary physical features to predict effectively those aspects of the ocean that are important for coupling with the atmosphere. Because of the highly successful Numerical Model Symposium in Durham, New Hampshire, in the fall of 1972, the third

session of our workshop on numerical modeling was not held. The proceedings of that symposium are being published separately by the National Academy of Sciences.

All four of the avenues of activity outlined must be carried out simultaneously because the results found in one are pertinent to the methodology adopted in the other, and it is necessary to develop each of them to successfully construct the ocean part of a good climatic predictive model. As knowledge in these four activities grows, trials can be made with certain numerical models that represent the ocean joined with the atmosphere to understand how accurately predictions can be made. One can adopt an optimistic view and suppose that, with the proper support and coordination of activity, preliminary joint models with some degree of predictive success will be operative within 10 or 15 years. Yet the task, an enormous and complicated one, will need firm support and a concerted effort to achieve such an end. At this stage, responsible scientists would not guarantee success.

CHAPTER 2

STATISTICAL STUDY OF EXISTING DATA: THE IDENTIFICATION OF CLIMATE FLUCTUATIONS

Both ocean and atmosphere are variable in space and time. Their interaction on a great variety of scales sometimes is such that scale conversions take place; that is, the very small weather scales may interact in such a way as to determine the larger climatic scales. Because of the necessity to compute the smaller scales in space and time so that averages may be taken to deduce climate, many of the problems associated with making numerical climatic models of the atmosphere develop. The problem is even more severe for the oceans because of the smaller scales which may contribute to the energetics of ocean climate.

A number of questions about the space and time scales of the atmosphere and the ocean need to be answered before one can construct appropriate models of the interaction process, many of which can probably be answered from the proper analysis of existing data.

1. Are there climatic regimes in the ocean; that is, does the character of fluctuations seen in ocean variables (e.g., North Atlantic surface salinity variations) change in a statistically meaningful way? Or do the changes in regime apparent to the eye consist of simple Gaussian red or white noise processes? One could approach this question through analysis of variance or more sophisticated stationarity and higher order moment tests.

2. If there are definable climatic changes in surface variables, are they local, oceanwide, or global in scale? What are the space-time scales of temperature and heat content fluctuations of the upper ocean? Is

there a well-defined isolated spatial scale (deep MODE eddies or surface NORPAX eddy scales)?

3. Does the atmosphere have any memory of the longer time scales in the ocean? The recent work of Lorenz and Leith implies that there is no memory longer than 3 days in point correlations of variables; yet Namias has found statistically significant pattern correlations at low frequencies, implying that there is an underlying large-scale memory. Can one reconcile these results? If there is a statistically significant memory, is it sufficiently great to improve climatic forecasts, or will the memory always be swamped by the natural large variability in any short-term realization of the atmosphere (Leith, 1973). How nonwhite (and, hence, how predictable) are atmospheric variables at periods longer than a week? Is the occurrence of a cold winter or a drought simply analogous to the unpredictable tossing of 20 "heads" in a row from a true coin?

4. Can one parameterize the small-scale eddies of the atmosphere in such a way that true climatological numerical models are possible? In existing numerical models can one detect realistic changes in imposed sea surface temperature? Do the atmospheric models extract realistic amounts of heat from the ocean?

5. Does the atmosphere have true climatic regimes? Stating it another way, is the atmosphere nearly nonergodic in the sense that some parts of phase space are reached much less often than others for a given set of external conditions? If such regions of space are preferred, are they separable over relatively short periods of time in numerical models?

6. Can the case-study-type hindcast, done by Namias, be used for forecasting? Based on standard tests of skill, how does a Namias-type forecast compare with simple persistence or climatological forecast?

CHARACTER OF CLIMATIC VARIATIONS IN THE ATLANTIC

Principal Temporal Characteristics

The historical data on the surface temperature of the North Atlantic has been archived principally from the active fishery areas north of 40°N latitude. Archiving and analysis of the data in the subtropics and tropics is still in process. Compiling the full North Atlantic sea-surface temperature (SST) record on magnetic tape would take one year according to the Meteorological Office, Bracknell. Single data series in the North Atlantic are the most extensive from any ocean, and both the International Council for the Exploration of the Sea (ICES) and the International Commission for the Northwest Atlantic Fisheries (ICNAF) have maintained separate records. The fact that national responsibilities have been centered on certain preferred areas has tended to hinder a Pan-Atlantic analysis of the data, in contrast to the work which has been carried out on the Pacific records.

Long-term trends of the surface water-mass characteristics vary considerably with observational location, indicating that spatial and temporal scales are coupled, often in different ways, depending on which parameters have been monitored. Long-term indices of change in the North Atlantic are not always most clearly apparent in the sea-surface temperature. In general, there has been a 20- to 25-year trend in cooling of the North Atlantic, particularly in the northern and eastern parts, although there has been some sign of reversal since 1971.

According to Dickson, strong, quasiperiodic, 4 to 6-year, interannual variations in the salinity and temperature appear superimposed on the interdecadal trend. The salinity variation is the strongest signal in all areas of the eastern Atlantic for which salinity records exist (North Sea, Ocean Weather Ship "M", etc.), but a similar change is encountered in the temperature variations from the far north (Ocean Weather Ship "M", Barents Sea). This salinity and temperature variation has been most evident since the 1930s, with a dominant 4 to 6-year periodicity found for the first quarter of this century. Five-year variations of opposite phase appear to be found in the temperature records from the northwest Atlantic, but the data quality here is not as good. Dickson's analysis of the salinity and temperature records from weather ship data (Norwegian Sea) shows that the 4 to 6-year trends are found to penetrate 200-300 m into the water column, and to at least 200 m from the temperature record of the Barents Sea.

Sea ice conditions have also been studied. Although short-term changes in ice extent obviously occur, they appear less systematic than the changes described above. It is probably more meaningful to describe the longer term interdecadal changes. There are strong correlations of long-term atmospheric circulation patterns with sea ice extent and with the salinity and temperature of the East Greenland/East Icelandic Current System. From 1958 to 1970, there has been a growth of pack ice north of Iceland (Greenland Sea) and a lowering of the sea surface temperature (Norwegian and Greenland Seas). Some amelioration of these conditions has reportedly occurred since 1970.

Principal Spatial Characteristics

Long-Term (Interdecadal) Changes. A number of spatial features of long-term variations have been tabulated in the North Atlantic. The dominant change appears to have been the persistent establishment of a high-pressure anomaly cell over Greenland (strongest in the winter months), bringing cold air from the Arctic toward Iceland and the British Isles. This high-pressure system seems to be correlated to increased sea ice formation in the western North Atlantic and to SST cooling from the Arctic to the North Sea Shelf. The high latitude blocking over Greenland is said to have arisen (post-1930) when the Iceland low and the Atlantic westerlies were at minimum strength (i.e., meridionality in place of zonality).

Interannual Changes. The dominant 4 to 6-year variations superimposed on these long-term variations apparently are associated with a particular recurrent atmospheric circulation anomaly of great persistence (up to 1 year). Specifically, this circulation anomaly involves an intensified trough over the west Atlantic with an associated ridge over Scandinavia, thus leading to a meridional distribution of sea-surface temperature (SST) anomaly (cold, west Atlantic; warm, east Atlantic). In contrast to the Pacific Ocean, which can contain three to four wavelengths of an atmospheric anomaly pattern, the Atlantic Ocean is half the size and contains barely two half wavelengths. There are a variety of intriguing (but as yet untested) similarities between hydrometeorological events in the Atlantic and Pacific sectors. It is important to note that if these similar events in each sector are related and are not merely similar behavior patterns occurring by chance, the influence need not necessarily be in the direction of mean atmospheric flow (Pacific-Atlantic). It is known, for example, that strong blocking in the Atlantic sector may propagate to the west, upstream on the jet stream system, and manifest itself in the Pacific. Thus, strong atmospheric circulation anomalies in the eastern North Pacific can be heralded (or controlled) by the North Pacific SST anomaly pattern and by North Atlantic blocking.

The 18°C water column in the subtropical northwest Atlantic, like the 17.6°C water column in the northeast subtropical Pacific, serves as a similar horizontal homogenizing pool for horizontal scales of long-term changes. The indices of long-term variations in the Gulf Stream front, however, 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 more pan-oceanic ordering (now under way), while the greatest need in the Pacific is for extending the length of the data series by continued diligent monitoring. (This latter perhaps would best be supplemented with salinity time-series, which appear to express interannual variations in a more sensitive way than SST in the temperate Atlantic.)

CHARACTER OF CLIMATIC VARIATIONS IN THE PACIFIC

Principal Temporal Characteristics

The weather patterns and sea-surface temperature (SST) patterns in the North Pacific appear to change regime on a roughly decadal time scale. In 1957-1958, a sharp transition occurred in which the Aleutian low pressure cell intensified and the jet stream arched farther north along the western coast of North America. The subsequent return of colder air masses resulted in a colder eastern seaboard. In 1970-1971, the reverse situation set in. These patterns have been documented from 700-mb heights, intensity of storms, and locations of storm tracks. A clear and persistent SST pattern of the same time scale is evident along the coast from California to British Columbia.

Superimposed on the dramatic change in regime, three to five-year fluctuations are present. These stand out most strongly in the western North Pacific and are correlated to the variation in the earth's rotation speed and with a variety of atmospheric indices. In the eastern North Pacific, shorter period variabilities appear as winter-to-winter SST anomalies. The statistical treatment of such features is based on spectral analysis with Kuroshio-Oyashio data. The features have been described principally as individual events in the eastern portion; an analysis of persistence, i.e., temporal correlation as a function of lag, has been computed in the entire North Pacific on the horizontal scale of 5° latitudinal x 5° longitudinal grid and is strongest in the eastern basin. The weak western correlations in Namias' data might be related to the fact that spatial scale features of the shorter period anomalies are not adequately resolved. As shown by Iida, not all long period anomalies have large scales.

Principal Spatial Characteristics

Studies so far have concentrated only on describing the sea-surface temperature (SST), but deeper features need to be described so that appropriate mechanistic explanations can be constructed as to how these patterns are linked to climate. The eastern North Pacific anomaly patterns appear to have a larger horizontal scale than the western patterns. The eastern patterns can be followed as they drift to the east over periods of 3 to 30 months. Namias and Dickson have shown significant lagged correlations in patterns in the eastern and central Pacific where 20° latitudinal x 40° longitudinal areas are considered. Iida has demonstrated correlations in the western North Pacific on a much finer spatial scale; the resolution in the eastern North Pacific has yet to be carried out on the scale of the Kuroshio-Oyashio system. The spatial scale changes in the atmosphere may be considered as long-term changes in wave number regimes of the atmospheric equilibrium across the globe. The 3- to 10-year shifts appear as meridional adjustments and seem to be compensated for around the globe.

The most persistent systems in the entire atmospheric pattern appear to be the Siberian high and a persistent cloud belt running south and east of Australia to the South American continent. Anomaly patterns, as described by the variance of the monthly means in the atmosphere, are most obvious over the eastern portion of the large ocean basins. The standard deviations of the monthly means of sea level pressures are five times higher in the Gulf of Alaska than on the eastern Asian coast. The statistical treatment of the SST data in terms of gross subjective aggregate patterns has advanced quite well in the North Pacific. A more objective analysis is needed [as demonstrated by small horizontal scale, long-period variability (Iida)], and the North Pacific Experiment (NORPAX) has undertaken this task. A subjective, synoptic Atlantic analysis is just beginning.

CHAPTER 3

MAJOR FIELD EXPERIMENTS SCHEDULED AND PROJECTED

THE CALENDAR

A series of cooperative programs - mostly national, although some international - have been launched to increase our understanding of the ocean in various specific ways. Overarching these oceanographic programs are the worldwide meteorological programs associated with the Global Atmospheric Research Program (GARP). Although primarily a meteorological research program, GARP contains certain experiments that offer great opportunity to oceanographers. The first of these, Global Atlantic Tropical Experiment (GATE), scheduled for June through September of 1974 in the tropical Atlantic Ocean, has received wide participation from oceanographers. A more extensive program under GARP, First Global GARP Experiment (FGGE), is planned for 1977-1978. Of special interest to oceanographers are the FGGE plans to measure the sea surface pressure and temperature from drifting buoys between 50°S and 65°S and to increase the meteorological coverage in the tropics during the Asian monsoon period.

These two areas of emphasis during FGGE will provide particularly rich opportunities for physical oceanographers in carrying out experiments. In Southern Ocean, for example, the dynamics of ocean currents is very obscure and poorly understood. Very large changes in transport of water through Drake Passage between South America and Antarctica have been observed, but are yet theoretically unaccountable. Because adequate coverage of wind data in high southern latitudes will be obtainable for the first time during FGGE, there will be an opportunity to compare variations in the wind stress as observed from the drifting buoys with variations of transport through Drake Passage as monitored by an array of pressure gauges and current meters.

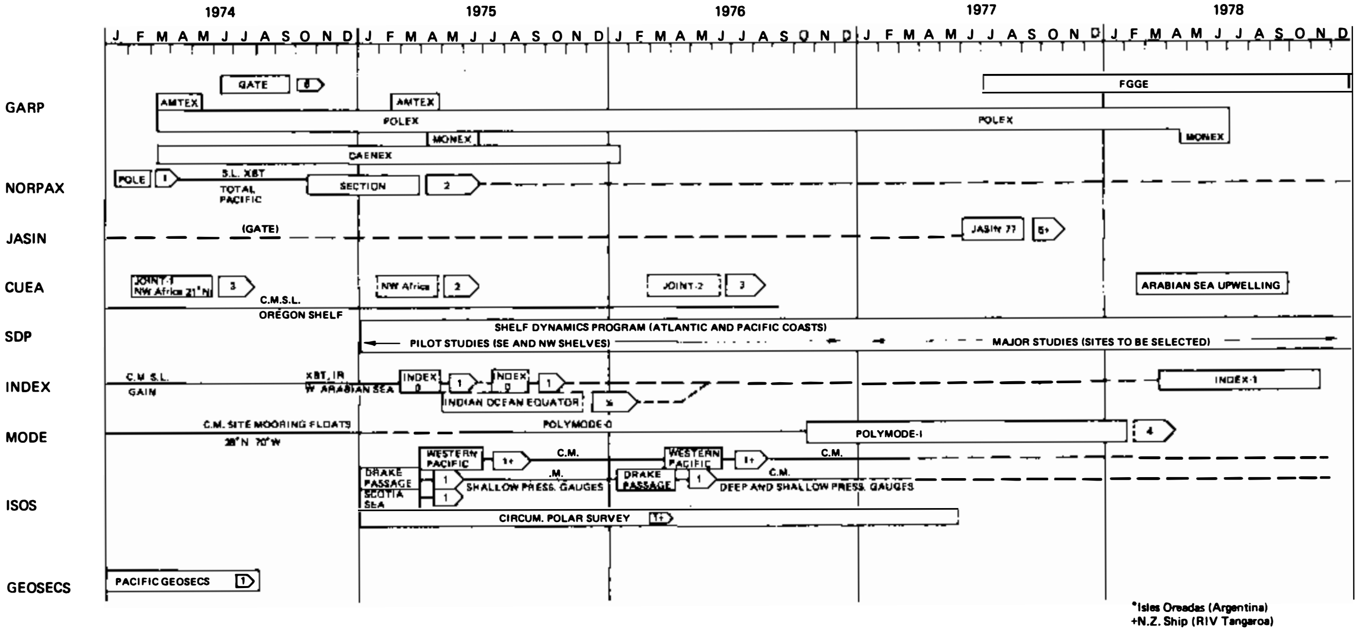

FIGURE 2. _ Calendar of field programs

The situation is quite the opposite in the monsoon areas of the Arabian Sea where some theoretical preparation for phenomena at low latitudes already exists. Theoretical ideas of the response of the tropical ocean to the changing winds of the monsoon and about the propagation of waves trapped along the equator have been worked out. The intense period of meteorological observation during the period of the southwest monsoon is indicated in Figure 2 by the box labeled MONEX, Monsoon Experiment. This actually refers only to the meteorological program being organized under GARP. As indicated in Figure 2, MONEX is expected to occur during May and June 1978.

The Air Mass Transformation Experiment (AMTEX) consists of two short expeditionary studies in the East China Sea and the adjoining regions of the Kuroshio Current off the Ryukyu Islands of Japan. Although not primarily an oceanographic experiment, AMTEX will attempt to determine some further details about the warming up of cold air from the Asian continent as it flows over the warm waters, particularly of the adjacent Kuroshio Current and the East China Sea.

The North Pacific Experiment (NORPAX) has many different programs. What we delineate in Figure 2 are the field programs associated with the process-oriented experiments of NORPAX, the first of which is POLE (implemented in the spring of 1974), to be followed a year later by a larger scale experiment in the North Pacific. Both of these experiments in NORPAX are aimed at delineating more clearly the horizontal scales involved in thermal anomalies both at the surface and with depth. Further field experiments will doubtless be planned for 1976 and the years following, although the details have not yet been determined.

The Joint Air-Sea Interaction Experiment 77 (JASIN), scheduled for 1977, is a United Kingdom initiated experiment on the mixed layer of the Atlantic Ocean that will continue a three-ship operation concluded in 1972. Both NORPAX and JASIN are aimed directly at unraveling some of the problems of measurement and of the physical processes operating in producing sea-surface temperature anomalies. Because NORPAX and JASIN both deal with an aspect of the ocean that may directly force atmospheric motions, they are particularly relevant to the ocean-atmosphere climatic modelling effort.

Coastal Upwelling Ecological Analysis (CUEA), its offspring Shelf Dynamic Program (SDP), and Indian Ocean Experiment (INDEX) attempt to study the effect of well-defined atmospheric forcing on the ocean. The oceanic upwelling phenomenon results from winds parallel to the coast that drive surface water offshore, thus causing deep cold water to surface. The current system in the Indian Ocean is also directly forced by the alternating monsoon. A clearer understanding of these oceanic cases, where the ocean is directly forced by the atmosphere in a time-varying fashion, would be helpful to test present conceptions of the dynamics of the ocean circulation.

CUEA has a continuing program of current meter and sea level measurement along the Oregon shelf and also a general program of geographical exploration of other upwelling areas throughout the world. The first of these areas is off the northwest African coast; there CUEA will join forces with JOINT I and other countries in early 1974. In the following year, the continuing northwest African work will be supplemented by a program off the coast of Peru. Continuing work is also scheduled under the name JOINT II for early 1976. Future FGGE programs, from 1977 to 1978, plan to extend the upwelling studies to the Arabian Sea which could include the strong upwelling regions off the coast of Arabia (Yemen and Oman), as well as regions off the coast of Somaliland, where the Somali Current is associated with a small but very strong upwelling region off Ras Hafun.

INDEX has been confined entirely to the Indian Ocean and more especially to the Arabian Sea. Since January 1973, weekly current meter measurements have been made on the equator at the island of Gan in the Maldives. It is anticipated that this key monitoring station will continue to be maintained during the course of the INDEX experiments through 1978. Tide gauges to measure sea level will also be installed on the African coast near the equator and on the island of Gan. XBT sections will be made across the Somali Current using tankers on the route from the Persian Gulf to the Cape of Good Hope, and infrared surveillance of the sea surface temperature of the western Indian Ocean will be maintained by special arrangements with the satellite operating agencies. Current experiments will be initiated in 1975 during two short visits by major research vessels from the United States and the United Kingdom indicated by INDEX O. These visits are scheduled to coincide with the monsoon season of 1975, thus making it possible to place moored instrumentation at the equator in March that will be recovered in July. In addition, a small vessel will be chartered for use from the Seychelles, which are less than a day's steaming from the equatorial site. It is intended that this chartered vessel be available during the 1975-1976 monsoon period for the purpose of current profiling and STD work on sections across the equator. Field studies, culminating in a program involving both the Somali Current and the equatorial regions in the Indian Ocean in 1977-1978, are designed to coincide with the intense meteorological work during FGGE.

The Mid Ocean Dynamic Experiment I (MODE) was completed in the spring of 1973. At present (Spring 1974), subsurface floats are still operating in the area and being tracked as are several site moorings occupied for the purpose of obtaining long time series at 28°N, 70°W. Preparation is under way for a major field experiement during 1977, called POLYMODE; this project, to be performed in conjunction with the Soviet Union, is to receive 50 moorings and 500 current meters from the Soviets. United States and United Kingdom scientists associated with the MODE I work are evaluating their results, and on the basis of this will determine whether an effective contribution in the large POLYMODE effort can be made. This type of study is apparently indirectly connected with the climate problem. It is believed essential, however, to understand the role of mesoscale eddies in the models for computing the general oceanic circulation.

International Southern Ocean Studies (ISOS) is a sequence of ocean dynamics and monitoring experiments in the Southern Ocean. The field program will begin in January 1975 with a major study in the Drake Passage - Scotia Sea aimed at the long-term variability and kinematics of the circumpolar current system. A moored array of current, temperature, and shallow pressure recorders will be deployed with the goal of a two-year time series. Hydrography, chemical measurements, and short-term current meter arrays will be used to estimate transports and path of the current, and to provide pilot data on the Polar Front zone in the Scotia Sea. Later monitoring of the flow through the Passage will include the use of deep pressure gauges and other integrating techniques. Two additional ISOS field efforts relate to the effect of Southern Ocean dynamics on the rest of the world ocean and thus global climate: A moored array of current and temperature meters is planned for the Antarctic Bottom Water boundary current in the Southwest Pacific (and later, the Southwest Atlantic) to monitor the variability of this northward flow, and a feasibility study is planned to assess the potential for future direct monitoring of processes responsible for Antarctic Bottom Water formation under ice.

Experiments with drifters tracking in the Circumpolar Current are expected to begin in late 1974. A series of drifter experiments will probably be maintained up to 1977, and redeployment on a larger scale will occur during FGGE in 1978. Some of the data necessary for preliminary descriptions of the oceaographic processes in the Southern Ocean are being collected by programs which are not directly part of ISOS, but are closely associated. These are: the completion of the circumpolar physical oceaographic survey, the Weddell Sea summer survey, and the hydrography of the water beneath the Ross Ice Shelf (part of the RISP Program).

Geochemical Sections Studies (GEOSECS) depicts long time scales and directions of motion of the deep and intermediate oceanic circulation from the distributions of the many different kinds of tracer that are being studied on a world scale. This important study is being carried out by geochemists, and at the time of this writing the Pacific section is reaching completion. The Atlantic study was completed last year, and the Indian Ocean section is planned for 1975 to 1976. The global nature of the GEOSECS surveys and the completeness of the coverage of many kinds of tracer make it a fundamental benchmark for future studies of oceanic circulation on the long scale and for inferences about the ultimate fate of pollutants introduced into the ocean.

Finally, the main field program for the Arctic Ice Dynamics Joint Experiment (AIDJEX) is scheduled for 1975. As indicated earlier, the thermodynamics and dynamics of the ice cover is an important ingredient in the ocean atmosphere climate model of the future.

THE LOCATION OF THE EXPERIMENTS

Figure 3 charts probable geographic distribution of the various projects over the world. The monitoring part of NORPAX covers the whole North Pacific Ocean, but in this section, we are mainly concerned with the process-oriented experiments. The central core for NORPAX, indicated by the small black square north of Hawaii, is a region of intense early exploration in 1974 and 1975. It is expected that this area will gradually be enlarged until 1978, when a much larger area will be investigated, an area roughly the size of a major thermal anomaly. A north-south line through the area indicates another possible configuration for experimentation between 1975 and 1978.

British initiated efforts in studying mixed layer dynamics are included under JASIN, indicated in the figure by capital J. Cooperation during GATE in 1974 in the Atlantic is indicated by the J in that area, and a more particular investigation with international participation in the North Atlantic is indicated for 1977. The GATE areas for investigation in the tropical Atlantic are shown to occur in 1974 by the three areas marked capital G. The continuing program of coastal upwelling studies of CUEA, beginning in 1973 and continuing indefinitely into the future, is indicated by C off the Oregon coast. Other areas of investigation are indicated for 1974 (off northwest Africa), 1975 (off Peru), and 1977 (Arabian Sea). The U.S./U.S.S.R. joint experiment called POLYMODE, planned for 1976, is indicated by capital P. The area of investigation of the response of the Indian Ocean current system to the monsoons, called INDEX, is indicated by the capital R. This program might begin in 1974 and reach a more intense FGGE related phase along the equator in 1976 to 1977. The area occupied by ISOS will initially cover the regions of intense study in Drake Passage, the Scotia Sea, and the abyssal western boundary currents as indicated by the capital letter S.

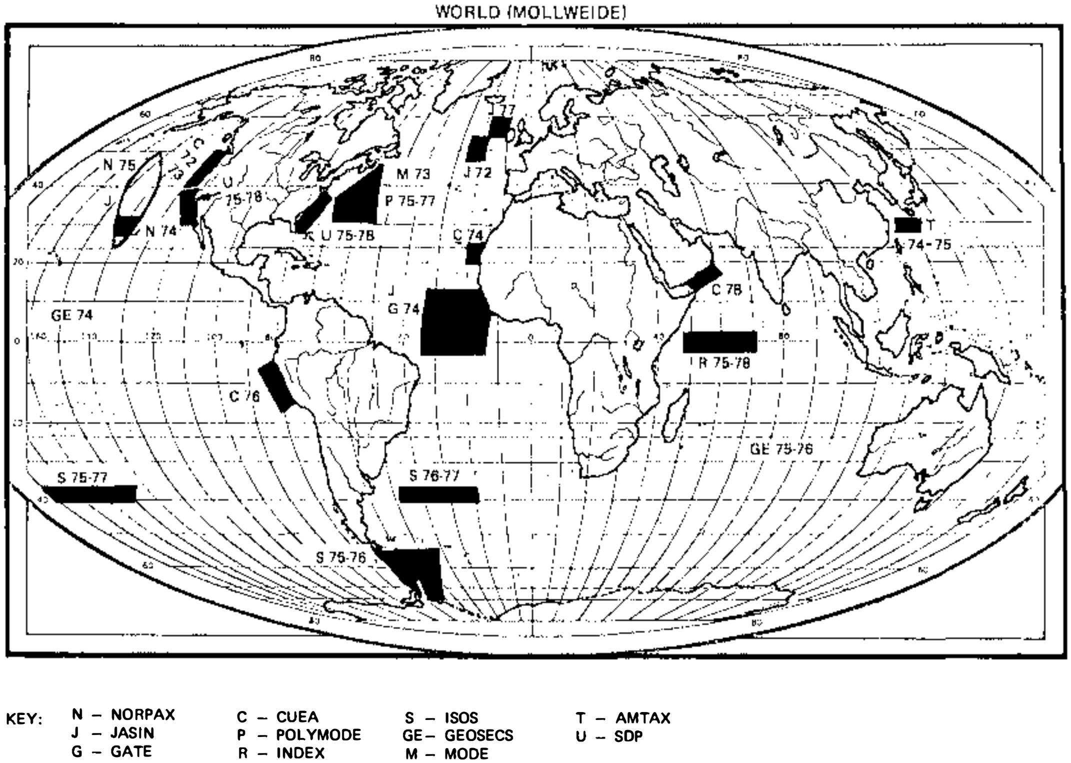

FIGURE 3. _ Probable geographic distribution of field experiments

FEATURES OF AND INTERACTION BETWEEN THE LARGE PROJECTS

The features of the large projects are listed in Table 1. During discussion at Workshop Session I, it was realized that the various large projects served each other in various ways: scientifically, technologically, and logistically. To make their relationships more explicit, written reports were prepared by each of the project leaders describing (i) how his project depended on other projects, and (ii) how he though his project could be useful to the others. The result of these reports have been condensed, edited, and summarized in Table 2.

TABLE 1 Features of the Large Projects

	Projects:
Main scientific objective	GATE: Determine fluxes for budget calculations in the mixed layer; to make use of the unique opportunity of having multiple ships deployed near equator
	NORPAX: North Pacific fluctuations on scales of months to years and greater than 1000 kms and their relation to atmosphere
	JASIN: To understand physics of small scale mixing and transfer processes in oceanic and atmospheric boundary layers
	CUEA: Predictive knowledge of ecosystems associated with upwelling processes
	SDP: To understand (model) time-dependent circulation and exchange on continental shelves
	INDEX: Determine response of ocean to large scale monsoon forcing, and relate to theory
	MODE/POLYMODE: Role of eddies in the dynamics of the general ocean circulation
	ISOS: Use southern ocean as laboratory for study and monitoring of large-scale dynamics and interaction; parameterize effects of large scale southern ocean processes into global circulation models
	GEOSECS: Global survey of the distribution of a large number of geochemical tracers
Immediate scientific objectives	GATE: 1) To study salt and heat budgets, internal waves, mixed layer development and shallow fronts [C scale]; 2) To study forcing of ocean by cloud clusters [B scale]; 3) Description of the Atlantic Equatorial Current system [A scale]
	NORPAX: 1) Analysis of existing sea-surface temperature and other routine data 2) Mixed layer dynamics; special field studies; numerical modeling
	JASIN: 1) Measure turbulent structure in velocity, temperature, and salinity in the mixed layer; 2) Describe processes in the mixed layer
	CUEA: Physical description and numerical modeling of upwelling
	SDP: 1) Understand response to meteorological forcing; 2) Measure coupling of shelf and deep ocean motions; 3) Compute vertical and horizontal exchange rates

TABLE 1 (continued)

Immediate scientific objectives (continued)	INDEX: 1) Measure propagation of distrubances along the equator; 2) Measure response of the Somali Current to monsoons; 3) Develop numerical theory to predictive stage MODE/POLYMODE: Kinematics of eddies; 2) Scales and statistics of eddies; 3) Dynamics of eddies; 4) Energy sources of eddies ISOS: 1) Dynamics and thermodynamics of the Antarctic Circumpolar Current System: establish response of current system to large-scale atmospheric forcing, resolve and establish the energy-containing space and time scales in selected regions; 2) Antarctic Bottom and Intermediate Water--formation and outflow: describe various processes at work at proper place and time, determine variability of northward flow of Antarctic Bottom Water in selected regions GEOSECS: Bench mark survey of the Atlantic and Pacific Oceans
Schedule of main field programs	GATE: June-September 1974 NORPAX: POLE: 1 month, Jan. 1974; SECTION: 3 months, Jan-March 1975 JASIN: JASIN 72: 1 month, 1972; JASIN 77: 6-8 weeks, 1977 CUEA: JOINT I, N.W. Africa: 3 months, 1974; JOINT II Peru: 3-4 months, 1976; Arabian Sea: 1977-78 [April-October] SDP: 1975-76, prototype monitoring network; 1976-77, major shelf wave experiment INDEX: Pilot programs 1975-76 [most intense March-July]; main FGGE program 1978 MODE/POLYMODE: MODE: 4 months, 1973; POLYMODE 0: 1975-76; POLYMODE I: 1976-77 ISOS: Drake Passage and Scotia Sea Study: 1975-76; completion of Circumpolar Survey, 1975--; Antarctic Bottom Water monitoring in Western Pacific, April 1975--- GEOSECS: Atlantic: 1972- ; Pacific: 1974; Indian: 1975-76

TABLE 1 (continued)

Monitoring schedule	NORPAX: Monitoring gradually built up over the years: tide gauges, etc. CUEA: Continuous monitoring off Oregon Coast, 1973-78 SDP: Selected east and west coast sites beginning 1975 INDEX: Continuous monitoring at Gan Island, site moorings, IR satellites, tanker XBT, and new tide gauges MODE/POLYMODE: Monitoring at various sites in Sargasso Sea, 1971-77 ISOS: Drake Passage currents monitored continuously 1975--; Antarctic Bottom Water northward flow monitored continuously 1975-- in western Pacific
Relation to climate	GATE: Direct through GATE NORPAX: Direct main objective JASIN: Physical processes which determine the sea surface temperature and heat storage in the upper ocean CUEA: Mostly local climate, El Nino SDP: Determine climatology of shelf circulation including evidence of influence from deep sea climatological fluctuations INDEX: Development of reliable equatorial models essential for coupling climate models to Bjerknes mechanism MODE/POLYMODE: Indirect, through necessity to model general circulation with physically correct deep-ocean model ISOS: Effect and response of Southern Ocean on local and global climate; development of polar climate models for input to global climate models GEOSECS: Limited prediction of climate changes
Relation to FGGE	GATE: This may be regarded as a logistic exercise for FGGE ship experiments NORPAX: Indirect, because FGGE is not intense in the North Pacific JASIN: Local and not simultaneous CUEA: Arabian Sea project is related to MONEX (FGGE) INDEX: Part of MONEX (FGGE)

TABLE 1 (continued)

Relation to FGGE (continued)	ISOS: Oceanographic input to FGGE southern ocean drifter program; use increased meteorological coverage of FGGE in southern ocean to help study of large-scale ocean response to atmospheric forcing. GEOSECS: Indirect
Participants U.S.	GATE: Miami, WHOI, URI NORPAX: SIO, Hawaii, OSU, University of Washington, Texas A&M JASIN: WHOI, Miami, OSU CUEA: OSU, FSU, MIAMI, PMEL/NOAA, University of Washington SDP: WHOI, MIT, Miami, Nova, OSU, FSU, University of Washington, JHU INDEX: MIT, Nova, Miami, AOML/NOAA, Scripps MODE/POLYMODE: WHOI, MIT, Harvard, Yale, AOML/NOAA, URI, Scripps, JHU, Columbia ISOS: Texas A&M, University of Washington, WHOI, OSU, Lamount, USC
Participants International	GATE: All GARP participating countries JASIN: UK, Fed. Rep. Germany, Holland CUEA: Liverpool, DHI, Spain SDP: UBC and various corresponding members INDEX: UK during pilot programs MODE/POLYMODE: UK, USSR ISOS: New Zealand
Sponsoring agency in U.S.	GATE: NSF NORPAX: NSF/IDOE, ONR CUEA: NSF/IDOE SDP: NSF/IDOE MODE/POLYMODE: NSF/IDOE, ONR ISOS: NSF/IDOE
Instrumentation	GATE: STD, Thermistor and Batfish tows, moored current meters, multiple ship NORPAX: Flip, overhorizon radar, STD, XBT, AXBT, IR (air-craft) CUEA: STD, moored current meters, small meteorological buoys SDP: STD, cycle-sonde, inclinometer strings, moored current meter pressure gauges, meteorological buoys

TABLE 1 (continued)

Instrumentation	INDEX: STD, satellite IR, XBT, tide gauges, moored current meters, ship-lowered velocity profilers MODE/POLYMODE: STD, moored current meters, sofar floats, profilers, bottom instrumentation ISOS: STD, moored current meters, shallow and deep pressure gauges, possibly drifters
Lifetime of project	GATE: 1972-74 NORPAX: 1972-- JASIN: 1970-- CUEA: 1973-- SDP: 1975-77 INDEX: 1974-78 MODE/POLYMODE: 1971-78 ISOS: 1974

TABLE 2 Relations Among the Large Projects

Information obtained in these projects	Useful to these
GATE	NORPAX: C-scale mixed layer information; knowledge of circulation; T JASIN : C-scale is experiment to precede JASIN 77; T CUEA: T ISOS: T INDEX: Equatorial dynamics and mixed layer modeling; T MODE/POLYMODE: Geographical distribution of eddies
NORPAX	JASIN: Large-scale mixed layer knowledge; T CUEA: Mixed layer modeling SDP: Mixed layer dynamics INDEX: T GEOSECS: Surface fluxes MODE/POLYMODE: Geographical distribuiton of eddies ISOS: Mesoscales in mixed layers; how to monitor large-scale circulation; T
JASIN	GATE: Information on mixed layer modeling NORPAX: Mixed layer knowledge, surface fluxes and parameterization CUEA: Mixed layer modeling SDP: Mixed layer dynamics MODE/POLYMODE: Surface signatures ISOS: Intermediate water formation at fronts monitoring of air-sea fluxes GEOSECS: Surface fluxes
CUEA	NORPAX: Eastern boundary current monitoring; extension of anomalies to shore; T SDP: Coastal upwelling dynamics; T; L INDEX: Similar dynamics; L ISOS: Coastal currents; current dynamics near shelf (including upwelling)
SDP	NORPAX: Extension of anomalies to shore JASIN: Mixed layer dynamics on shelf ISOS: Bottom water formations GEOSECS: Ocean shelf exchange processes CUEA: Annual cycle and secular variations in shelf circulation; boundary processes; T

TABLE 2 (continued)

Information obtained in these projects	Useful to these	
INDEX	NORPAX: Time dependent models for equatorial circulation CUEA: Similar dynamical problems; L SDP: Response to meteorological forcing	MODE/POLYMODE: Geographical distribution of eddies ISOS: T
MODE/POLYMODE	NORPAX: SST signatures; general circulation modeling capability, T JASIN: Advection of mixed layer by eddies	INDEX and ISOS: T GEOSECS: Physics of large-scale Turbulent transport
ISOS	NORPAX: Methodology for monitoring frontal zone; teleconnections between southern ocean and tropical circulation CUEA: Current dynamics near shelf; upwelling in icy regions; interaction of wind with upwelling	INDEX: T MODE/POLYMODE: Geographical distribution of eddies GEOSECS: General description of southern ocean
GEOSECS	NORPAX: Isotope determination of time responses in mixed layer JASIN: Isotope determination of time responses in mixed layer CUEA: Basic chemistry	MODE/POLYMODE: Evidence of end results of horizontal mixing ISOS: Tracing of bottom water formation

NOTE: T - Technological development of measuring systems

L - Logistical support

CHAPTER 4

THE NEED FOR A WIDER COLLECTION OF ROUTINE DATA AND THE PROSPECTS FOR NEW REMOTE-SENSING TECHNIQUES

It has been amply demonstrated that the circulation and structure of the combined ocean-atmosphere system undergoes changes within time frames that range from weeks and seasons to years and longer. As soon as time scales larger than months are involved, associated space scales or teleconnections are probably global. These changes can only documented and studied through the use of a global monitoring network. Although we consider ocean and atmosphere as one intimately interlinked system, in this section the monitoring of the ocean and its surface will be stressed.

A MONITORING SYSTEM: CRITERIA AND PURPOSES

An ocean-atmosphere-climate monitoring network will have to serve two basic purposes: (1) collect coherent data on long-term parameters representative of large areas in order to document and study long-term changes and (2) gather synoptic data with direct immediate access in order to forecast weather, sea conditions, and thermal structure in the upper ocean.

Processes To Be Monitored

Monitoring in itself is not sufficient unless the monitoring system is designed to give information relevant to a study of the processes that govern and cause climatic changes and events. The most important aspects to be studied include the following:

1. Surface meteorology to give information on the processes of energy transfer between ocean and atmosphere in the form of momentum and heat exchange and thus on the

forces driving ocean circulation and changing ocean structure;

2. Subsurface thermal structure of the ocean to yield a measure of heat storage and its changes in the ocean and the possibility to infer by geostrophy the amount of advection in the ocean; and

3. Circulation to be monitored to assess its changing intensity and advection and to test the performance of theoretical ocean-atmosphere models.

Coverage

For the purpose of monitoring and studying the long-term changes of the ocean atmosphere system it is essential to employ a worldwide monitoring system. As presented earlier, in the long run each subsystem is affected by or affects the other subsystems. For the study of processes linking the various subsystems, it may be possible to restrict monitoring to certain closely linked subsystems. Although this approach may not be possible with regard to the atmosphere, it may very well be feasible in studying the responses of a particular enclosed ocean basin such as the North Pacific to atmospheric forcing and the related feedback. For such studies a more intensive network in a particular region might be advantageous for research purposes. The oceans of the southern hemisphere are probably not suitable for such an approach since they are significantly interlinked.

Nevertheless, at present the southern hemisphere is the most poorly monitored part of the world. In view of the desirability of a global monitoring system, the observational effort in that region should be greatly increased.

When considering the monitoring of such a huge and complicated system, one might ask whether monitoring of selected features and links in the system might suffice. For example, the monitoring of the most energetic components may yield information about the largest signals. It should be noted, however, that the most energetic components of the circulation may be at quite different locations than the areas of the largest signals in heat storage. Many parameters are sufficiently diffuse in their geographical distribution that only a coherent areal coverage will give the desired information.

coherent areal coverage will give the desired information.

Parameters To Be Monitored

Table 3 lists the parameters now monitored, the platforms used, the space coverage, frequency of observations, and information delay. Also included are a number of systems that are in an experimental stage of development.

New Systems

Development of new systems of monitoring should aim at designing methods that integrate over space or time. Examples are: 1) free drifters giving trajectories over large areas and long times, 2) measurements of waves and currents by means of radar backscattering, which average over sizeable areas, 3) measurements of acoustical travel time that could give mean temperatures or mean currents over large distances, 4) special sensors for direct measurement of accessible heat storage of the upper layer, 5) methods for measuring total transport of strong currents, and 6) full utilization of the power of geochemical tracer distribution techniques particular for abyssal circulation.

Subsurface Temperature Structure

The most pressing problem is the monitoring of the subsurface temperature structure, the key parameter in the scientific analysis of the changing ocean. Moreover, it is an essential parameter in forecasting the sound velocity structure. The problem is aggravated by the withdrawal of the ocean weather ships and by the fact that the number of XBT observations taken by ships of opportunity is also declining. After the loss of the weather ships, subsurface temperature observations can only be collected by ships of opportunity using XBT's, by aircraft using AXBT's and from anchored or drifting buoys. Each of the systems has its inherent advantages and disadvantages. Ships of opportunity deliver data along given routes, in most cases at fairly regular intervals, leaving large areas outside the main shipping routes uncovered. Aircraft are more expensive to operate, but will supply data wherever directed. They are especially suitable to experiments covering areas outside the shipping routes. Moored buoys are the ideal oceanographic replacement for the ocean weather stations insofar

SUBJECT	PLATFORM	SENSING: DIRECT OR REMOTE	FREQUENCY OF OBSERVATIONS	COVERAGE	ACCESS DELAY	INSTRUMENT	PROBLEMS
Radiation	Land and island stations	D	Continuous	Local	Month	Radiometer	
	Satellite	R	Daily	Global	Day	Radiometer	
Weather: pressure temperature, wind, clouds, humidity, rain	Land and island station	D	6 h	Local	Radio	Conventional instruments	
	Weather ship						
	Buoys	D	Continuous	Local	Radio		
	Ships of opportunity	D	6 h	Regional	Radio		
Clouds	Satellite	R	Daily	Global	Day	Radiometer Photography	
Sea surface temperature	Ships of opportunity	D	6 h	Regional	Radio		
	Satellite	D	Daily	Global	Days	Radiometer	
Waves	Ships of opportunity	D	6 h	Regional	Radio	Estimates	
	Satellite	R	Daily	Global	Day	Radar scattering	
	Radar	R		Regional			

TABLE 3 (continued)

SUBJECT	PLATFORM	SENSING: DIRECT OR REMOTE	FREQUENCY OF OBSERVATIONS	COVERAGE	ACCESS DELAY	INSTRUMENT	PROBLEMS
Wind	Satellite	R	Daily	Global	Day	Radar scattering	
	Radar	R		Regional			
Currents	Ships of opportunity	D	Daily	Regional	Year	Ships drift	
	Satellite	R	Daily	Regional	Day	Drifting buoys	
	Radar	R		Regional		Over horizon radar	
Temperature structure	Ships of opportunity	D	6 h	Regional	Radio	XBT	
	Weather ships	D	6 h	Local	Radio	BT, STD	
	Buoys	D	1 h	Local	Radio	Profiler	
	Aircraft	R	Hourly	Regional	Radio	AXBT	
Sea Level	Station	D	Continuous	Local	Months	Tide gauge	
	Satellite	R	Daily	Global	Days	Radar altimeter	

as they produce continuous time series data at given spot but do not provide the upper air data. The relative value and importance of time series data at a fixed spot versus a periodically repeated section have still to be investigated and may depend considerably on the geographical region and the problem investigation. Drifting buoys taking temperature profiles will be useful only if deployed in large numbers, and they are randomly distributed in space. The best results may derive from using a mix of the various systems: Ships of opportunity to monitor a network of standard sections, aircraft to fill gaps in this network, and moored buoys to obtain time series in the center of large uncovered areas.

A Possible Alternative to the Ocean Weather Station Program

Over the past 25 years the Ocean Weather Stations of the Atlantic and Pacific sectors have constituted the most complete data base for the study of ocean/atmosphere variation in open ocean areas. However, the expense of maintaining these stations has now brought about a drastic reduction in the network and, although data buoys have been suggested as replacements, these too will be expensive to maintain, even in limited numbers. Certainly, they do not offer a solution to the problem of data collection over the great expanse of tropical and southern oceans. Over the majority of the world ocean, our knowledge of ocean climate variations is based largely on surface data collected by the commercial ship reporting programs, a means of data collection that is too random in space and time to establish the fixed-point time series required. Without disrupting the current commercial ship reporting program, a part of this sampling effort could be reshaped to provide a *constant frequency of subsurface sampling at fixed locations* and at a low. These commercial ships would act as Phantom Weather Ships.

Our rationale is as follows: In world shipping there exists a number of major companies operating large fleets of bulk carriers (tankers, ore carriers) that operate between *fixed* points of supply and demand. Accordingly, they occupy relatively fixed routes at a rather constant frequency. In essence, we plan to identify each major fleet in this category, whether or not they are currently contributing ocean data, and for each fleet we will then seek to identify the precise routes and traffic frequencies worked by their vessels.

Initial inquiries with three major fleets (Shell, B.P., and Exxon) have shown the existence of several routes worked by each company at a frequency of over six voyages per month; it is clear that if a sufficient number of these routes can be identified globally and if observations can be arranged at carefully chosen times and points along these routes, we are approaching the type of fixed-point data collection networks that the weather ships used to provide (but in this case on a global scale). The location of each site will be critical since no major carrier will agree to divert its vessels from its preferred route. Thus, while each station should be located in a hydrographically critical or representative site, the normal routing patterns of vessels (current routing, weather routing, etc.) must also be studied in detail if the system is to be practicable. In addition, as we now envisage the scheme, *each major carrier will be responsible not for a chain of globally distributed stations* (which would impose impossible restrictions on the navigation of their vessels) *but 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. Thus, from 50-100 major bulk carrier fleets we would plan a global network of perhaps 100 stations. Already some 50 potentially suitable fleets have been identified, some running in sparsely sampled areas (Japan - South America or Japan - Australia, for example). As regards the parameters to be sampled, perhaps the minimum program should involve XBT, surface temperature and salinity, the normal meteorological parameters, and solar radiation measurements.

Cost Analysis

Since cost is an important decision-making factor in operating a monitoring network for an extended period of time, a cost analysis for obtaining observations of sub-surface temperature structure by three different modes is presented.

1. Ships of Opportunity. These are merchant ships that make routine observations along regular routes, as for example, one section taken 24 times per year with 25 XBT observations per section. If operated as part of a larger program (about 6 to 8 sections), the cost will

be about $30 thousand per section or $50.00 per observation. Advantages: Regular network of repeated section, coverage of large areas, and relatively low cost. Disadvantages: Data concentrated along the main shipping routes, and large areas uncovered.

2. Airplane with AXBT. For example, one airplane taking 6 sections with 50 AXBT's 16 times per year. Cost of program is about $1.7 million or $280 thousand per section, or $330 per observation. Advantages: Sections can be chosen to cover any location, good areal coverage, and regular network. Disadvantages: High cost.

3. Moored buoy. The cost per buoy, based on operating at least six buoys that take a vertical temperature profile at 6-hour intervals throughout the year, is about $300 thousand or $190 per profile. Advantages: Continuous time series at a fixed location. Disadvantages: No spatial coverage unless a sufficiently dense network is used.

This analysis shows that the ship of opportunity operation, although not the most thorough, is the most economical. Under different assumptions, one might arrive at a somewhat different cost for the three approaches, but their relative cost seems to be rather firmly established.

Implementation

A globally planned monitoring system is essential to provide the necessary data for a realistic climate model which will compute the future climate and verify the predictions made in the recent past. In view of the differing advantages and disadvantages of the three modes of data gathering and of their different cost, it will be necessary to use a mix of the three modes to achieve maximum results. It is suggested that the main effort should be in establishing a sufficiently dense network of routes traveled by ships of opportunity. This network will inevitably leave certain parts of the ocean uncovered, these areas should be filled by observations from moored buoys delivering continuous time series at fixed locations. For certain specific areas, where coverage by a regularly repeated section is required rather than observations at isolated buoy positions, the airplane AXBT section provides the only possibility of achieving such coverage. It may be a necessity across current systems like the North Pacific Current, the equatorial current systems in the eastern Pacific, or the Antarctic Circumpolar current, where no regular ship traffic takes place.

Temperature profiles along sections and at buoy positions provide possible geostrophic transports inference and thus will contribute to the monitoring of the changes in circulation. In certain areas of the oceans, networks of sea-level gauges may be used as a very inexpensive means of monitoring the changes of sea surface slope across major ocean currents, since the sea surface acts as a very welcome integrator for the geostrophic flow.

There is little doubt that an oceanwide monitoring program will not be implemented at once; it will grow over a long period of time. In view of the ongoing research on large scale fluctuations of the ocean atmosphere system and of the growing interest in changes of our environment, it is important to continue the existing small monitoring effort, to strengthen it, and to enlarge its coverage and density. Operational moored buoys have been developed. It is now necessary to deploy them not only to fill gaps in the spatial data coverage but to gain experience about their use in a monitoring network. Since the weather ships will soon be withdrawn, it appears especially timely to replace some of them by buoys, possibly with some overlap in time to assure a continuity of the time series obtained by the weather ships.

It might be argued that it is advisable to concentrate the monitoring effort first in the oceans of the northern hemisphere, in particular in the North Pacific, where an initial monitoring network already exists and where a large research project (NORPAX) on long-term changes is in progress, and that after experience has been gained in the interpretation of data from such a network, it should then be extended to other parts of the world oceans. A counter argument for global coverage might also be made. The economics and logistics will probably be deciding factors.

Monitoring of the ocean could be improved if it becomes possible to:

1. Expand the existing network of XBT sections by ships of opportunity.

2. Replace several weather ships by moored buoys and implement the Phantom Weather Ship idea discussed on pages 35-36.

3. Start a network of moored buoys in the North Pacific on an experimental basis in order to gather experience with such a monitoring network.

4. Continue to improve existing meteorological and sea-level observations on isolated islands.

5. Encourage the development of new methods to monitor space and time integrating variables.

Processes of Interest for Climate Monitoring	Meteorology, Air-Sea Interaction Fluxes,	Surface Oceanography, Structure of Mixed Layer Ice Formation, and Variability Upper Layer Heat Storage	Deep Circulation Climatic Baseline for Deep Water
Radiation	Radiometer		
Weather	Conventional Instruments		
Clouds	Radiometer, Photography		
Wind	Satellite photo, sounding local radar		
Ice		Satellite photos, microwave, local estimates, satellite radar scattering	
I, $\int \rho c \rho t \Delta z$		Satellite infrared, ship of opportunity XBT, regular sections STD, moored arrays, ship of opportunity XST, regular sections STD	Moored arrays STD, XTD sections, AXBT
Velocity		Drifting floats, radar scatter	Moored arrays, drifting floats, STD sections
Pressure: Sea Level		Tide gauges, satellite altimeter	

APPENDIX TABLE 1 (continued)

Processes of Interest for Climate Monitering	Meteorology, Air-Sea Interaction Fluxes,	Surface Oceanography, Structure of Mixed Layer Ice Formation, and Variability Upper Layer Heat Storage	Deep Circulation Climatic Baseline for Deep Water
Deep pressure			STD sections, deep pressure gauges
Transports $\int v \Delta x \Delta z$		Shallow p-gauge acoustic measure	Deep pressure gauges, acoustic measure, E-M measurements
Radioactive and other chemical tracers (integrate dynamics, intergrate small = scale mixing)		Short-lived isotypes, other tracers	Long-lived isotopes, other tracers (nutrient chemicals)

APPENDIX TABLE 2 Conventional marine climatological data

Dry-Bulb Temperature

1. Monthly means

2. Frequency table in 3 °C steps based on the intervals 0.0 to 2.9 °C (postive values), -0.1 to -3.0 °C (negative values), or where and when necessary in 1 °C steps based on the intervals 0.0 to 0.9 °C (positive values), -0.1 to 01.0 °C (negative values)

3. Include extreme values when 3 °C steps are used as above

4. Standard deviations if the number of observations is sufficiently large

5. Monthly number of observations

Sea Temperatures

1. Monthly means

2. Frequency table in 1 °C steps based on the intervals 0.0 to 0.9 °C (postive values), -0.1 to -1.0 °C (negative values), e.g., 9.0 to 9.9 °C, -1.1 to 02.0 °C

3. Monthly number of observations

Visibility

1. Number of observations for each month for each code figure 90-99 (WMO Code No. 4377)

2. Monthly number of observations

Weather

1. Monthly number of occasions with rain or drizzle at the time of observation [ww = 50-67, 80-82 (WMO Code No. 4677)]

2. Monthly number of occasions with snow or snow and rain at the time of observation (ww = 68-79, 83-86)

APPENDIX TABLE 2 (continued)

3. Monthly number of occasions with hail at the time of observation (ww - 87-90)

4. Monthly number of occasions with thunderstorms at the time of observation (ww = 17, 91-99)

5. Monthly number of observations with (i) gales [Beaufort force = 8], (ii) storms [Beaufort force = 10], (iii) hurricane force winds [Beaufort force = 12] at the time of observation

6. Monthly number of occasions of precipitation at the time of observation (ww = 50-97, 99)

7. Monthly number of occasions of visibility less than 1 km

8. Monthly number of observations

Wind Direction and Force

1. Monthly number of observations for each month for each Beaufort number 0, 1, 2, etc., and for divec direction by sectors of 30 degrees, true north bisecting the first sector

2. Monthly total of observations for each sector irrecspective of wind force

3. Monthly number of observations for each Beaufort number irrespective of direction

4. Monthly number of observations

Pressure

1. Monthly means and extremes for all hours of observation

2. Frequency table in 4-mbar steps, based on the intervals 0.0 to 3.9 mbars, e.g., 996.0 to 999.9 mbars

APPENDIX TABLE 2 (continued)

3. Standard deviations if the number of observations is sufficiently large

4. Monthly number of observations

Cloud

1. Monthly mean of total cloud amount

2. Monthly mean amount for low cloud only [defined as cloud for which h is any code figure from 0 to 8 inclusive (WMO Code No. 1600)]

3. Monthly number of observations in the following ranges of total cloud amount (i) 2 oktas or less, (ii) 3 to 5 oktas inclusive, (iii) 6 to 7 oktas, (iv) 8 oktas

4. Monthly number of observations

Waves

1. List of original observations or, where number of observations is sufficient, seasonal tables may be prepared as indicated in paragraph 4.10 of the Annex of Rec. 36 (68-CMM)

APPENDIX 3:
LIST OF ABBREVIATIONS

AIDJEX - Arctic Ice Dynamics Joint Experiment

AMTEX - Air Mass Transformation Experiment

AXBT - Aircraft Expandable Bathermograph

CUEA - Coastal Upwelling Ecological Analysis

FGGE - First Global GARP Experiment

GEOSECS - Geochemical Sections Studies

GATE - Global Atlantic Tropical Experiment

ICES - International Council for the Exploration of the Sea

ICNAF - International Commission for the Northwest Atlantic Fisheries

INDEX - Indian Ocean Experiment

ISOS - International Southern Ocean Studies

JASIN - Joint Air-Sea Interaction Experiment

JOINT I - Joint Air Sea Interaction

MODE - Mid Ocean Dynamic Experiment

MONEX - Monsoon Experiment

NORPAX - North Pacific Experiment

POLYMODE - Polygon Mid Ocean Dynamic Experiment

SDP - Shelf Dynamic Program

SST - Sea-Surface Temperature

XBT - Expandable Bathermograph