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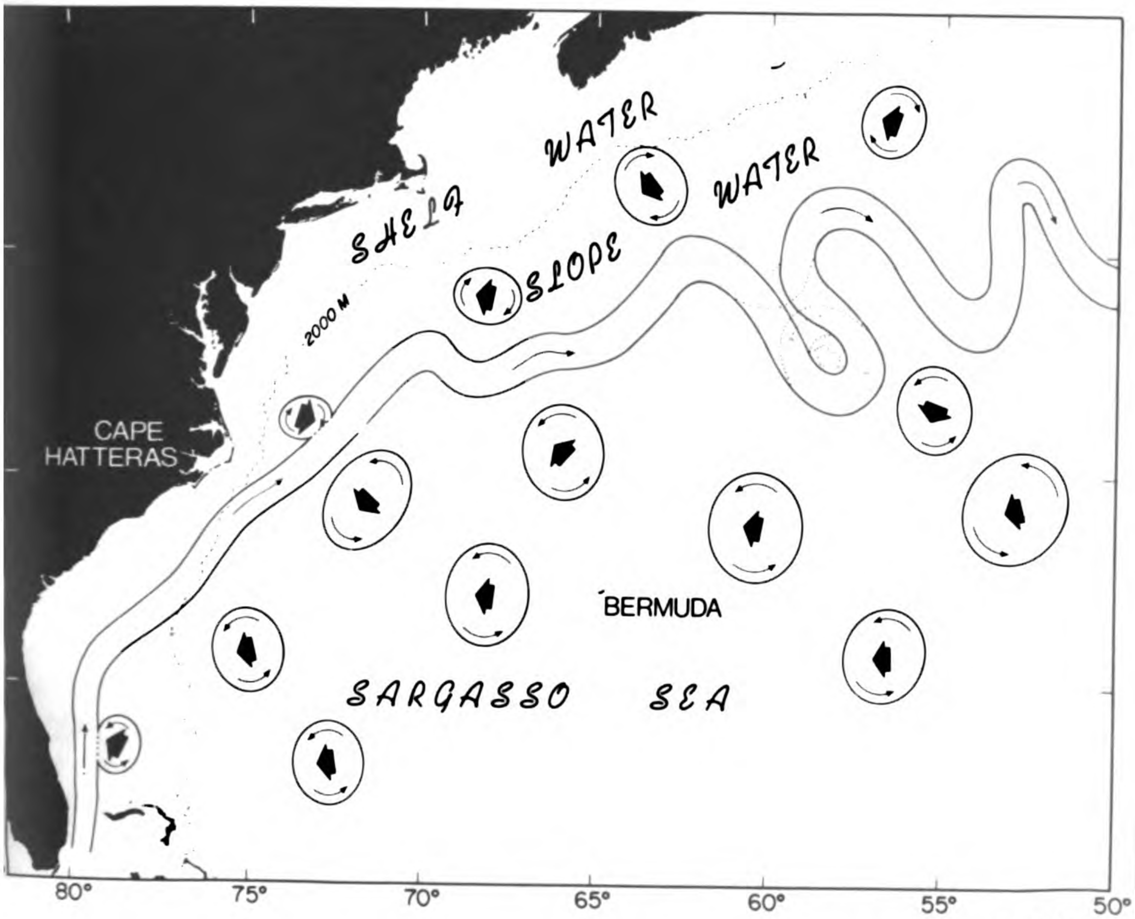

PROFILES IN SCIENCE

Professor Carl Wunsch

Professor Carl Wunsch is a prominent physical oceanographer at M.I.T. He is well known for using the linear wave theory to explain the results of sea-going observational programs. Dr. Wunsch has contributed significantly to the theory of internal waves, tides, and equatorial ocean circulation dynamics. He was awarded the prestigious James R. Macelwane Award by the American Geophysical Union in 1971 and the lucretive Texas Instruments Foundation Founders Prize in 1976. Since 1967 Dr. Wunsch has been an ONR contractor. He is a fellow of the Royal Astronomical Society and the American Geophysical Union. Dr. Wunsch has accepted a leadership role in the field design of the POLYMODE experiment in the North Atlantic and the INDEX experiment in the Indian Ocean.

NORPAX and the Upper Ocean

Klaus Wyrtki*
University of Hawaii

Introduction

The idea of a North Pacific Experiment originated from the work of Namias (1,2,3), who demonstrated that anomalies of sea surface temperature have a pronounced effect on the circulation of the overlying atmosphere and on the weather downstream. He showed in the example of the North Pacific that large sea surface temperature anomalies would lead to changes in the path of the cyclones and to displacements of the path of the jet stream. The displacement of the jet stream would in turn affect weather conditions over the continental United States for months to come. Consequently, Namias claimed, observations of sea surface temperature in the North Pacific allow a reasonable prediction of the long-range weather and climate conditions over North America for months in advance.

The purpose of the North Pacific Experiment (NORPAX) is to learn more about the large scale interactions between ocean and atmosphere, and to understand the processes that govern these interactions. This understanding may in turn be used for predictive purposes. First, it is necessary to analyze the influence of one system on the other, namely the effects of the ocean on the atmosphere and the effects of the atmosphere on the oceans, before feedback mechanisms between the two systems can be studied and therefore, more learned about the internal dynamics of the coupled system. While the atmosphere affects the ocean dynamically through wind stress and thermally through heat exchange, the ocean affects the atmosphere almost exclusively through heat exchange. While the atmosphere is variable from day to day, as is obvious from the weather, the great heat reservoir of the ocean changes only very slowly. This implies that different time scales are involved in each system. The ocean will react only to the accumulated effects of many weather patterns, but the persistent storage of heat in the ocean will exert long-lasting effects on the atmosphere.

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Heat Anomalies

It has been learned that anomalies of sea surface temperature, which can be charted from the thousands of marine weather observations reported every month by ships, are not restricted to the sea surface. In fact, surface temperature anomalies are only the surface expression of anomalies in the temperature distribution of the upper layer of the ocean; these anomalies often extend to more than 100-meter depth and represent anomalies of the ocean heat storage. This stored heat can in turn be made available to the atmosphere to drive its circulation. Consequently, it would be of great interest to learn more about the reasons for the formation, maintenance, and decay of these heat anomalies in the upper layer of the ocean.

There are three different ways in which heat anomalies can be formed in the ocean. The first is through direct heat exchange with the overlying atmosphere. Strong winds and dry air masses moving over the ocean will cause excessive evaporation and will cool the upper layer. Weak winds, on the other hand, will withdraw little heat from the ocean and will allow radiation from the sun to warm the upper layer. The cloud cover also has an appreciable influence on the amount of radiation that reaches the sea surface. The heat used for evaporation is the most variable factor in the heat exchange through the sea surface because it depends on wind speed, which by itself is highly variable; strong winds causing a high rate of evaporation will result in abnormal cooling of the upper layer. In the tropical ocean, variations in the cloud cover may also influence the heat budget and the formation of heat storage anomalies.

A second possibility exists in particular in the mid-latitudes of the North Pacific Ocean, as well as in similar locations in other oceans, where many of the large heat anomalies are observed. In mid-latitudes a strong north-south gradient of sea surface temperature is usually present, and the prevailing winds are from the west. Since the wind-induced Ekman transport is to the right of the wind in the northern hemisphere, one can expect that stronger-than-normal winds will shift the surface water to the south. As a result of southward transport of surface water, the entire pattern of sea surface isotherms will be displaced southward, resulting in an apparent heat storage anomaly in the upper layer of the ocean. Although no heat has been removed from the water, a temperature anomaly has been created by lateral advection of water.

The third possibility involves the dynamics of ocean circulation in the entire North Pacific basin, and in particular those of the subtropical anticyclonic gyre. The northern branch of this gyre is the North Pacific Current, which is in essential geostrophic balance. Warm water is on its southern side and cold water on its northern. Isotherms and lines of equal density slope sharply upward from south to north throughout the upper 1000 meters of the ocean. Their tilt is a measure of the strength of the current. Consequently, changes in current strength will cause changes in the tilt of the isotherms and the appearance of a temperature anomaly in the upper layer. Thus, changes in the strength of the entire subtropical gyre, as well as long baroclinic waves in the North Pacific Current, may cause temperature anomalies. Such changes in the strength of the gyre may have their origin in regions other than that of the North Pacific Current; therefore, the resulting heat anomalies are not locally generated but are due to remote influences on the entire circulation system.

In summary, heat storage and surface temperature anomalies of large extent may have three different causes:

1. Local generation by surface heat exchange.
2. Local generation by lateral advection of the temperature pattern.
3. Remote or local generation by variations in ocean circulation and long baroclinic waves.

In many cases, as often happens in nature, all three forms of generation will, at different times and to different degrees, be responsible for the formation of heat storage anomalies in the ocean.

The Anamoly Dynamics Study

One of the important tasks for NORPAX is to determine how, and under what conditions, these different mechanisms operate. For this purpose a sub-program, the Anomaly Dynamics Study, has been created. This program has two long-range goals: one monitoring, and the other, scientific. The monitoring goal is to map the variability in the large-scale density and geostrophic velocity structure of the North Pacific Current from 30-50N, 150W-170E for a period of several years, with semi-monthly time resolution and a 5° square space resolution. The scientific goal is to understand the dynamical processes resulting in the large-scale response of the geostrophic flow in the North Pacific Current to transient wind forcing by the overlying westerlies.

Recent NORPAX studies indicate large-scale space and time changes in the behavior of the relative geostrophic flow in the North Pacific Current. White (4) has found that the large-scale relative transport of the geostrophic flow in the upper 500 m fluctuated by as much as 50% of the climatological mean with a time scale of about 5 years (Figure 1). More recently, White (5) has found evidence of large-scale meanders (approximately 10,000-km wavelengths) developing in the quasi-zonal flow regime of the North Pacific Current in association with these low frequency changes in overall relative transport. These current meanders

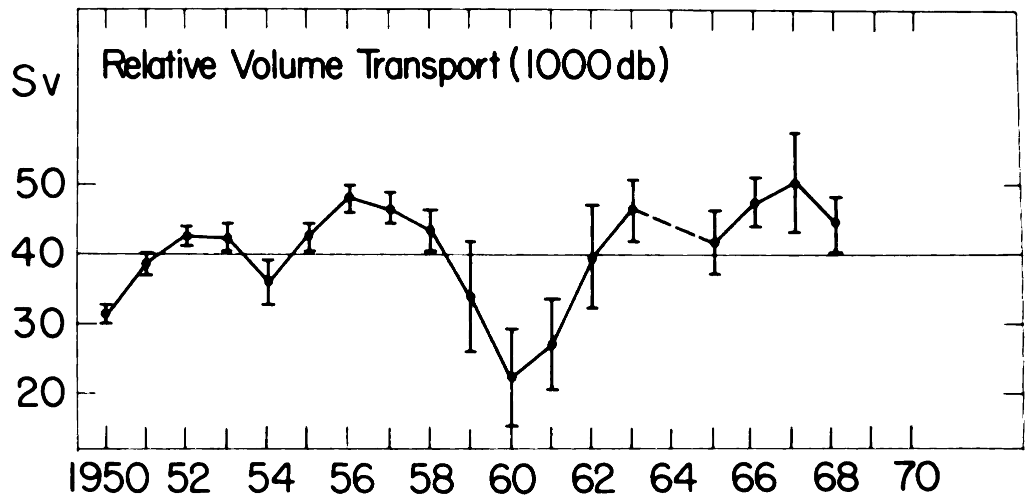


Figure 1 — Twenty year time sequence of the relative transport of the North Pacific Current (in Sverdrups, $10^6\ m^3s^{-1}$).

are associated with large north-south displacements in the main pycnocline by as much as ±4° latitude about the climatological mean latitude. This north-south displacement of the density field is manifested at the sea surface as intense large-scale sea surface temperature anomalies, which have been observed by Favorite and McLain (6).

Meso-scale waves and eddies have been detected in the North Pacific by Bernstein and White, (7); they have a typical wavelength of 500 km and a period of from 3-5 months. The generation and evolution of these waves is an interesting problem, but research indicates that they have little or no effect on the larger-scale variability and, therefore, they are treated in the TRANSPAC and XBT airplane programs only as a noise source. The experimental design of these XBT programs has been to oversample somewhat so that these mesoscale waves can be low-pass filtered out of the data.

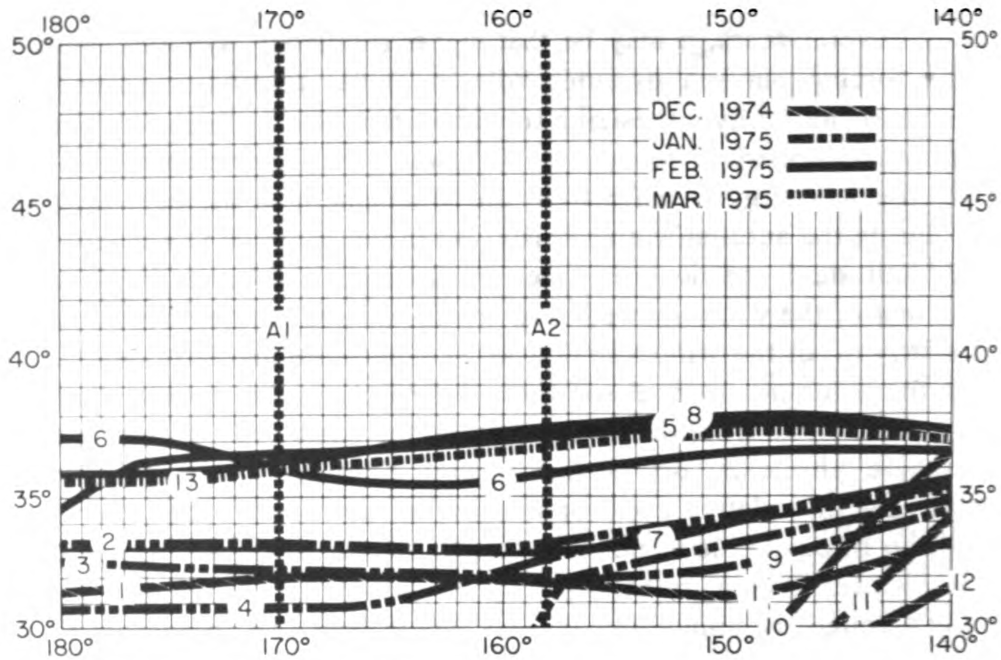
From these studies, the central question that arises is: how are these low-frequency, large-scale, changes in the relative geostrophic flow in the North Pacific Current generated? Presently, we believe that they are induced by short-term climatological changes, on the order of years, in the overlying westerly wind system. This belief derives from the view that the North Pacific Current is basically wind-driven, and that the year-to-year changes observed in the strength and location of the North Pacific Current are similar to those observed in the overlying westerly wind system (White, 8). However, relatively little is known about the physical coupling between the westerly wind system and the North Pacific Current. Existing time dependent, wind-driven, ocean theories do not account for the observed changes in the ocean.

Therefore, it appears that a different, more dynamic approach is necessary to the study of how changes in the North Pacific Current are induced by the overlying westerlies. While it is true that changes in the relative geostrophic flow in the North Pacific Current are associated with low frequency variability in the westerly winds on a time scale of several years, it may be that higher frequency, synoptic, atmospheric forcing plays a dynamic role in actual momentum transfer.

The rationale for hypothesizing this important role for high frequency synoptic atmospheric forcing is as follows. First, approximately 80% of the kinetic energy transfer from the atmosphere to the ocean takes place during the autumn/winter season when the synoptic storm activity at mid-latitude is particularly intense. Second, it follows from considerations of the wind-squared drag law for air-sea momentum transfer that nearly all of the wind kinetic energy enters the mid-latitude ocean during the autumn-winter season through synoptic storm activity. These facts indicate that synoptic storms may be the basic scale on which the atmosphere physically drives the general circulation at mid-latitude, namely that the relative geostrophic flow in the North Pacific Current is built up through a sequence of synoptic storm "impulses" during the autumn-winter season, rather than by a quasi-steady continuous wind forcing through the annual cycle. This would lead one to suspect that year-to-year changes in the autumn-winter synoptic storm activity may be responsible for the observed anomalous low-frequency changes in the relative geostrophic flow in the North Pacific Current.

First evidence from the recent TRANSPAC and airplane expendable bathythermograph (XBT) field program supports the hypothesized role of synoptic storm activity in altering the horizontal density structure and the relative geostrophic flow of the North Pacific Current. In the TRANSPAC field program, repeated quasi-zonal XBT sections have been made between North America and Japan from 30-40N during the winter of 1974-75, using ships-of-opportunity as launching platforms. Marine observers were placed on board these ships of opportunity, thereby allowing XBT data to be taken in a rapid sample mode, one per hour at approximately 40-km spacing across much of the mid-latitude North Pacific. During the period January 1955 – January 1976, 50 such sections were made. In the airplane field program, repeated meridional XBT sections were made between Hawaii and Alaska along 158W and 170W, once each month since November 1974. Figure 2 shows the locations of some of the quasi-zonal and meridional sections made from January to April 1975 by both the TRANSPAC and airplane XBT field programs.

Of particular importance in Figure 2 are three of the more northerly quasi-zonal sections (5,6,8). The three temperature sections are displayed in Figures 3a, 3b, and 3c. The first and second of these sections



| 46 W, 12/25 - 12/29/75, Van Buren
2 42 W, 1/5 - 1/9/75, Taft
3 43 W, 1/18 - 1/23/75, Mc Kinley
4 46 E, 1/20 - 1/23/75, Van Buren
5 47 W, 2/2 - 2/6/75, Van Buren
6 42 E, 2/2 - 2/6/75, Taft
7 43 W, 2/15 - 2/19/75, Taft
8 43 E, 2/15 2/19/75, Mc Kinley
9 U.S.N.S. 1/28 - 1/31/75, Silas Bent
10 12/13 - 12/14/74, Hawaiian Queen
11 12/22 - 12/23/74, Hawaiian Queen
12 1/28 - , Californian
13 43 E, 3/15 - 3/19/75, Taft
A1 11/11, 12/14/74, 1/14, 2/11/75, Barnett
A2 11/9, 12/11/74, 1/11, 2/8/75, Barnett

Figure 2 — The location of quasi-zonal tracks made during the TRANSPAC and the airplane XBT programs during January — April 1975.

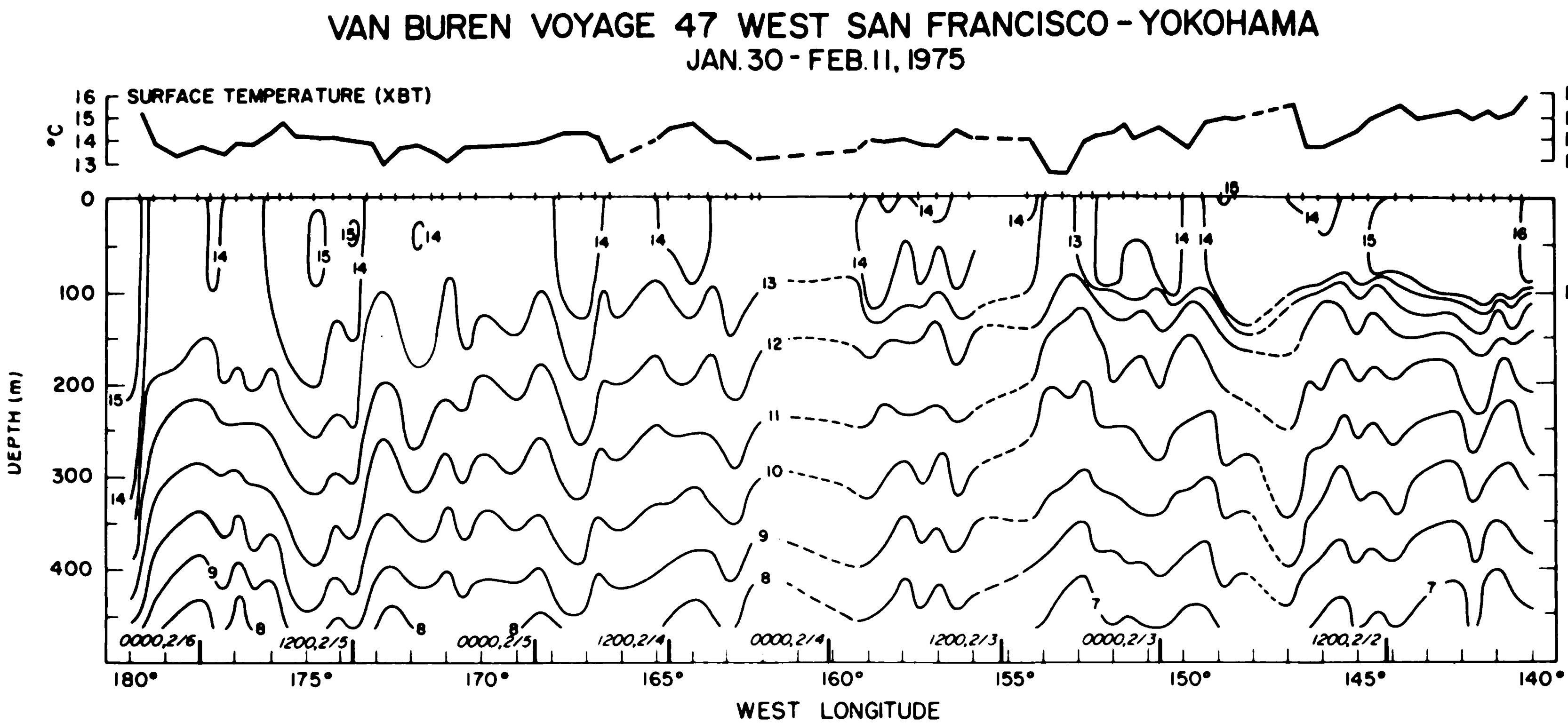


Figure 3a — Zonal vertical section (track 5 in Figure 2) of temperature along approximately 37N.

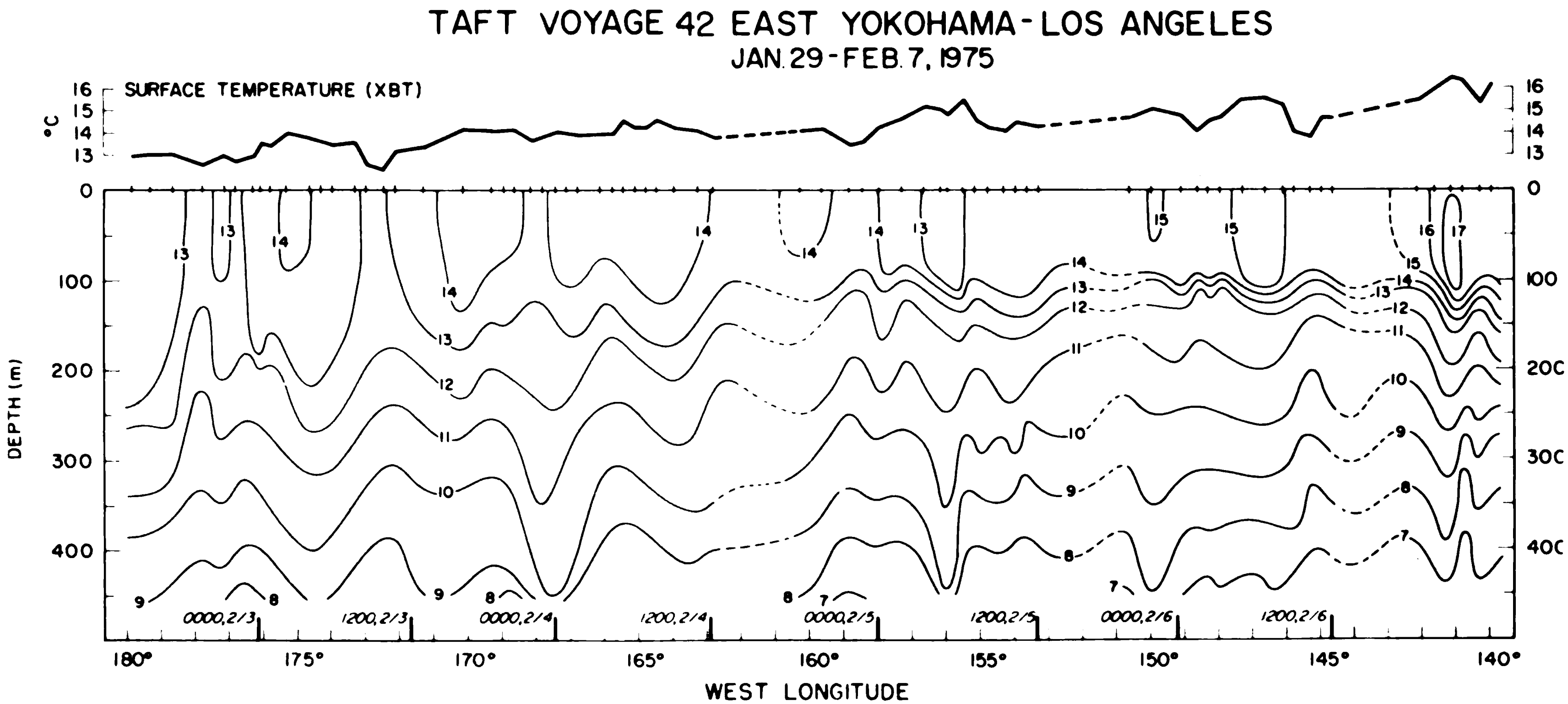


Figure 3b — Zonal vertical section (track 6 in Figure 2) of temperature along approximately 37N.

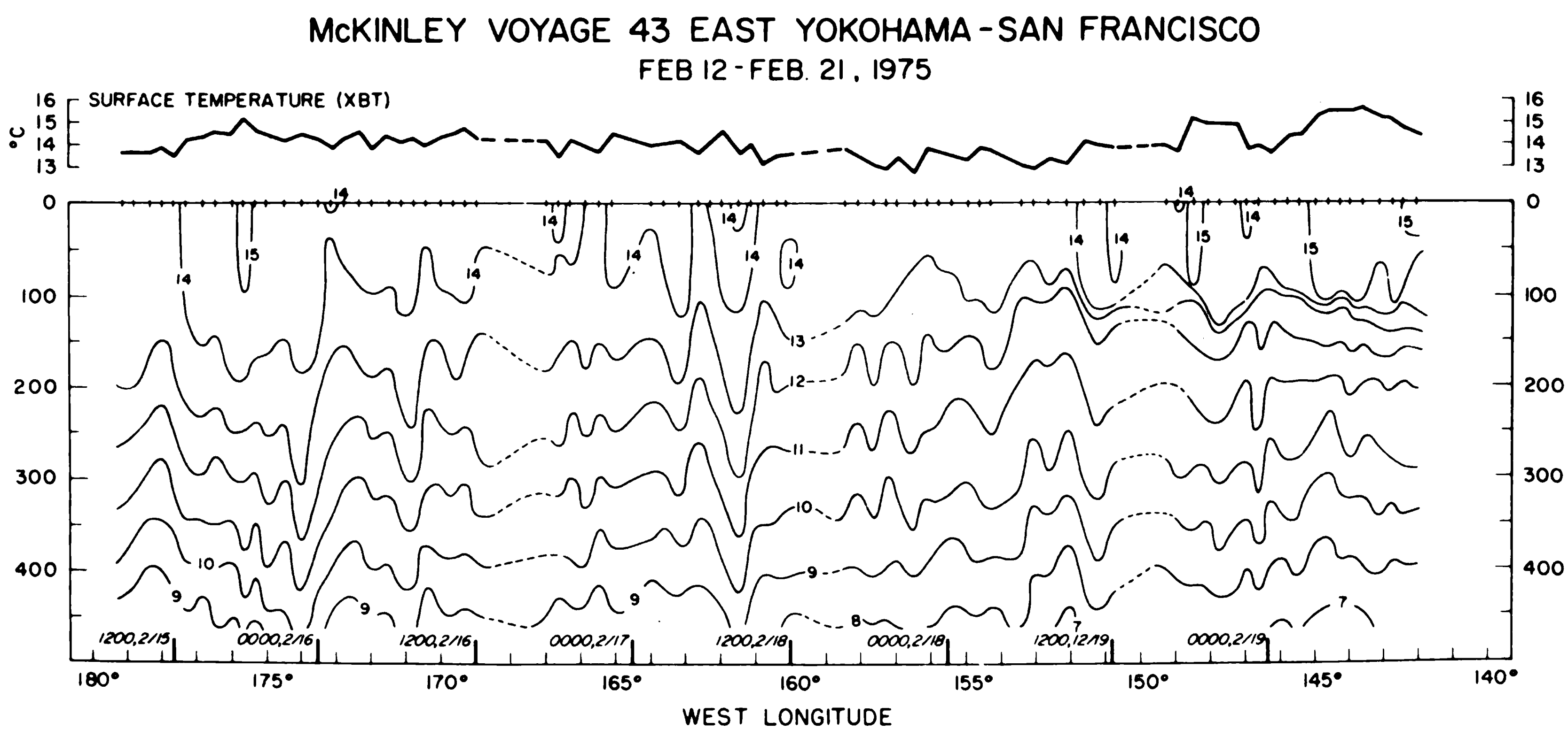


Figure 3c — Zonal vertical section (track 8 in Figure 2) of temperature along approximately 37N.

were obtained nearly simultaneously in time, but separated by 1 to 2 degrees latitude. The first and third of these sections had a two-week time separation, but with latitude separation less than 1/4 degree. The 10C and 12C isotherm depths, which are representative of the main thermocline, are compared in Figure 4a and 4b for these two pairs of sections.

From the lower panel in Figure 4a, it is apparent that the simultaneous sections show general agreement between 155W and 175W despite the 1 to 2 degree latitude separation. Both the 10C and 12C isotherms for the northern section (dashed curve) lay somewhat deeper than the more southern section (solid curve) between 155-175W, the mean difference being 7 ± 6m (St. dev. = 33m) and 14 ± 5m (St. dev. = 26m), respectively. These differences are relatively small. On the other hand, the two-week separated section (Figure 4b), with only 1/4 degree latitutde separation, show generally a downward displacement in depth of 30 ± 3m (St. dev. = 16m) in both the 10C and 12C isotherms between 155W and 175W. This represents a significant change in the large-scale structure of the main thermocline in the North Pacific Current over a two-week period. On both sides of this longitudinal band, the mean differences were much less.

Upon further investigation of this deepening of the thermocline structure, it was noted that the region located directly north of the latitude of these two sections had undergone intense storm activity during the two-week period, with one particularly strong low pressure system having remained for 3-4 days between 155-175W. This low pressure system was centered at about 45N, with a diameter of about 3000 km, containing a maximum wind speed of about 20m/sec. It seems possible that this storm activity could have induced the change in thermocline depth observed in the sections to the south between 155-175W; yet, it would have required the storm activity at 45N to have induced significant response in the form of downwelling along its southern flank over a period of less than two weeks.

To test whether this was theoretically possible, the problem was modeled using a two-layer quasi-geostrophic, prognostic model where the thermocline is the infinitesimally thin boundary layer between the upper shallow surface layer and the deep lower layer. The model conserves potential vorticity and is non-linear. The synoptic geostrophic winds over the mid-latitude North Pacific for this two-week time period were used as input. The stress was computed using the wind squared drag-law, with a drag coefficient of 1.5×10^{-3}.

In general, the model results show, as expected, that directly under the storm track across the mid-latitude North Pacific, upwelling occurs on the order of 15m/month, tending to form the subarctic gyre; to the south of the storm track near 35N, near the sections in Figure 4, downwelling exists. To determine how the model downwelling compares

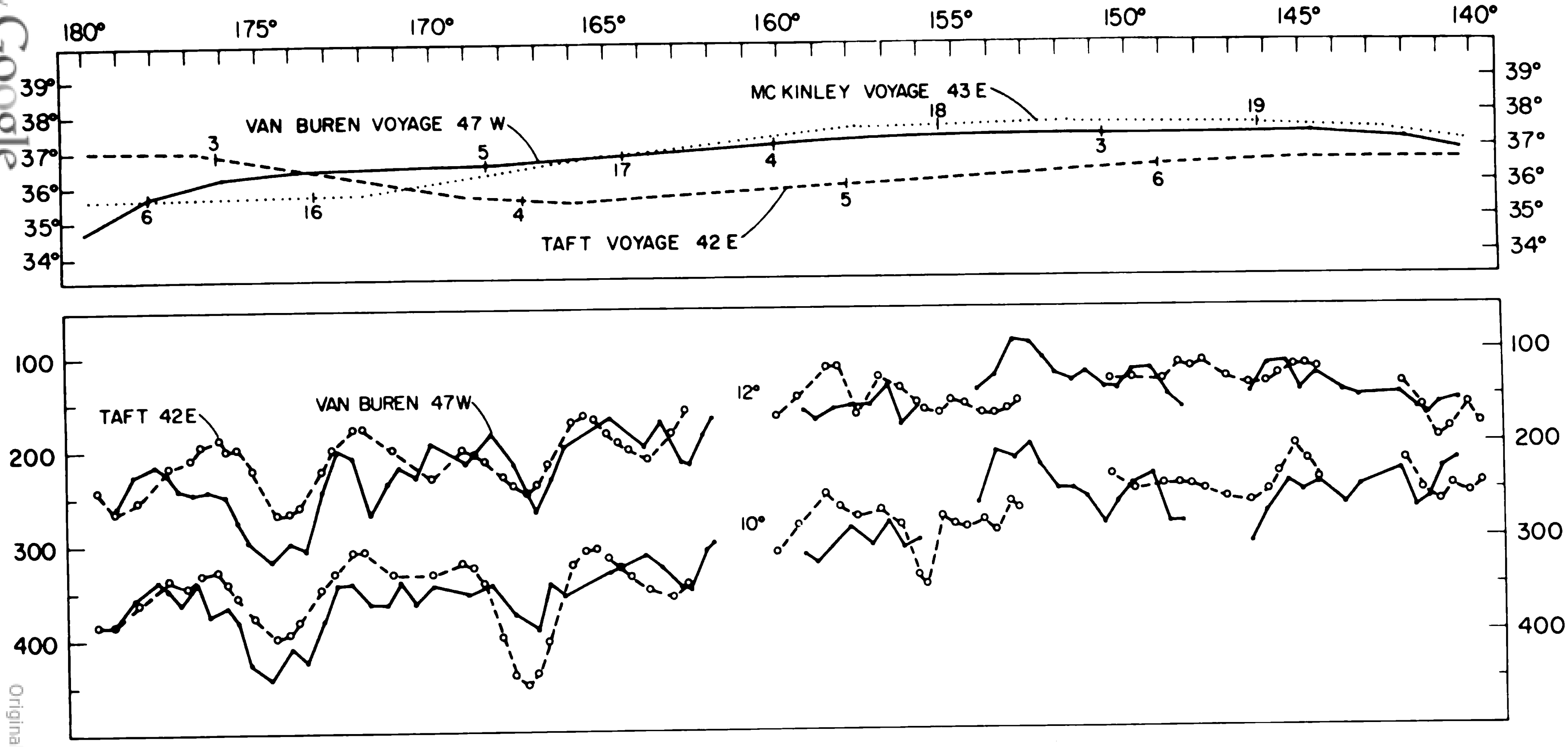


Figure 4A — The locations of tracks 5, 6, and 8 are shown in the upper panel. The 10°C and 12°C isotherms from 140 W to 180 for tracks 5 and 6 are shown in lower panel

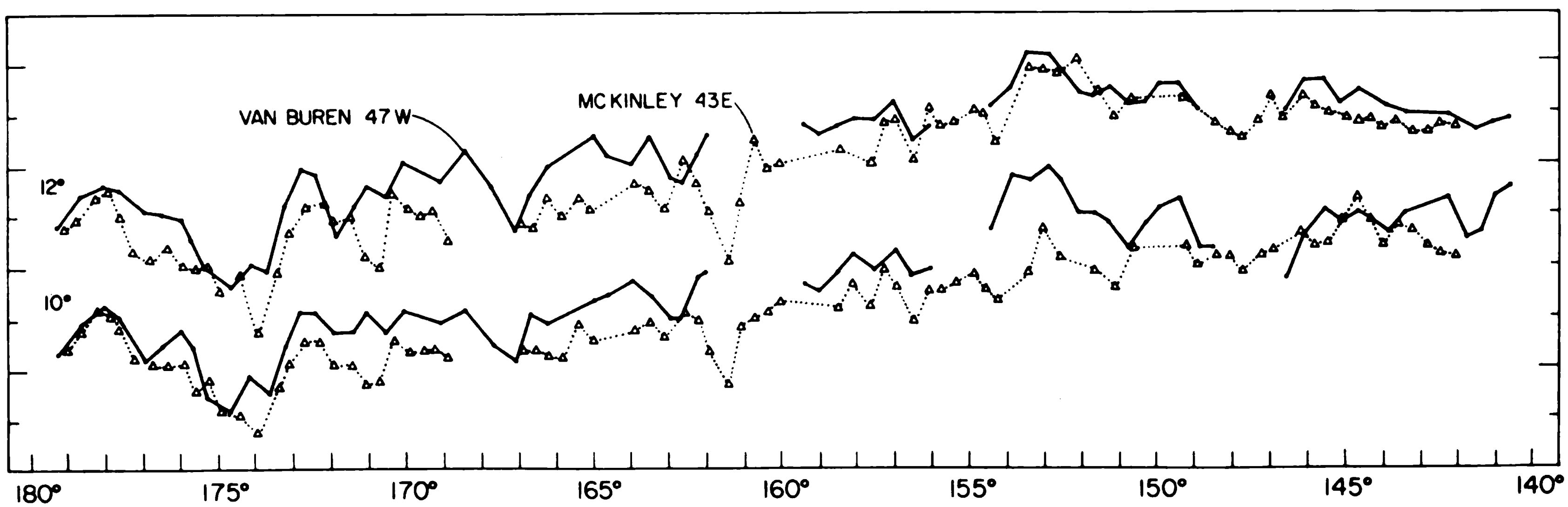


Figure 4b — The 10°C and 12°C isotherms from 140 W to 180 for tracks 5 and 8.

with that observed, the observed change in depth of the 10°C isotherm over the two-week period are plotted in Figure 5 together with that produced in the model. Qualitatively, the model results agree well with observation. Over the longitudinal range from 150W-170W, large relative downward motion occurred, with little or no change on either side. However, quantitatively, the magnitude of change in the model is approximately 1/5 of the observed, probably due to poor spatial resolution in the synoptic wind maps together with our lack of knowledge concerning the momentum transfer across the air-sea interface during storm conditions.

These experimental and model results are intriguing. They support the hypothesis that synoptic storm activity is an important mechanism in altering the relative geostrophic flow field in the North Pacific Current. If, in subsequent experimentation, these preliminary results are confirmed, they will point to the need for future investigation of the year-to-year changes in relative geostrophic flow in the North Pacific Current in terms of year-to-year changes in storm statistics or related dynamical quantities.

Sea Level and Ocean Circulation

In order to monitor, describe, and understand the movements of large pools of water in the oceans, in particular, those with an anomalous heat content, it is necessary to monitor the currents in the upper layer of the ocean. This task is difficult because of the high variability of currents in time and space and because of the presence of numerous eddies. Conventional methods of current measurements, such as current meter

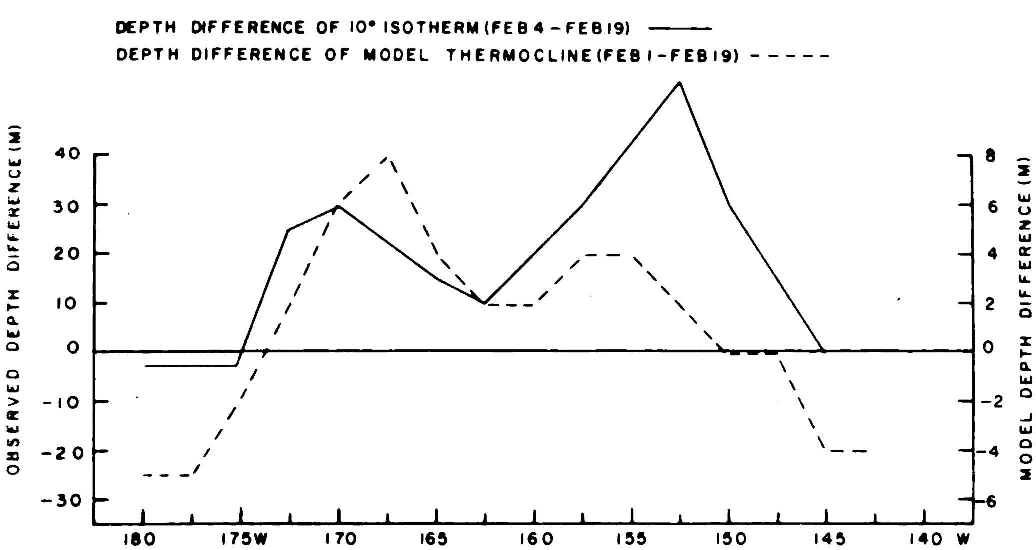


Figure 5 — Depth difference in the 10° isotherm and the model thermocline from February 1 – February 19 along 37.5N from 140W to 180.

moorings and GEK measurements, are not capable of providing the necessary information at a reasonable cost. The MODE project has clearly demonstrated how great an effort is required to obtain a detailed picture of the movements in the oceans over just a comparatively short period of time and a small area. For the study of the movements of large pools of water, one is, however, interested not so much in knowing the details of the flow, but their integrated effects after a certain time—the net results.

Ocean circulation is essentially in geostrophic balance, insofar as the flow field and the field of mass, given by the distribution of density, are strongly coupled. A knowledge of the distribution of mass allows computation of the geostrophic flow as well as the topography of the sea surface and other surfaces of constant pressure. This knowledge has been used in oceanography for a long time. The measurements of temperature and salinity at hydrographic stations have been used to determine density, calculate from it the geostrophic currents and the transports of entire ocean currents. Moreover, these geostrophic currents represent the mean velocities between hydrographic stations, and are, therefore, especially suitable for the purpose of describing the movements of water masses. In addition, the field of mass changes only slowly in the ocean and, therefore, geostrophic currents are somewhat conservative with respect to time.

Hydrographic surveys of large areas of the oceans to determine geostrophic flow require many ships and are consequently very expensive; there is no doubt that this method cannot be used to monitor the changing ocean circulation over large areas and over long periods. Other methods have to be used. Two survey methods presently being exploited in NORPAX are (1) measurements of the changing topography of the sea surface by means of sea level gauges and (2) computation of dynamic topographies using XBT observations as a substitute for hydrographic stations.

Changes in ocean circulation are reflected in changes of sea level, and the differences in sea level between pairs of observation stations can be used to compute the geostrophic surface current between them, as shown by Dietrich (9) and Wyrtki (10). In order to use this method to monitor ocean circulation, NORPAX during the last two years has established 20 new sea level stations on Pacific islands in addition to the few existing stations. The changes of mean daily sea level, although only a few tenths of a meter over periods of weeks to months are small, but reflect rather significant changes of ocean circulation.

Sea level and its fluctuations at an island can only be observed relative to an arbitrary zero point, so to compare sea level at different islands it is necessary to refer the various zero points to each other. The mean dynamic topography of the ocean, as computed from the vertical profiles of density, offers the proper reference surface. We have acquired from the National Oceanographic Data Center all the hydrographic observations for the Pacific Ocean, have computed the dynamic height for each station and have constructed a mean map of dynamic topography (Figure 6) as well as maps for the different seasons (11). This map shows the main features of ocean circulation in the Pacific, the large gyres, and the system of ridges and troughs in the equatorial region. Equating the mean dynamic height at each sea level station with the mean sea level observed at the station gives a common reference surface. We can then study the deformation of the sea surface at a given time by distorting the topography of mean sea level with the deviations of sea level from the mean as observed at the various gauges.

This technique has been used in conjunction with historical sea level data to reconstruct the fluctuations of the equatorial currents in the

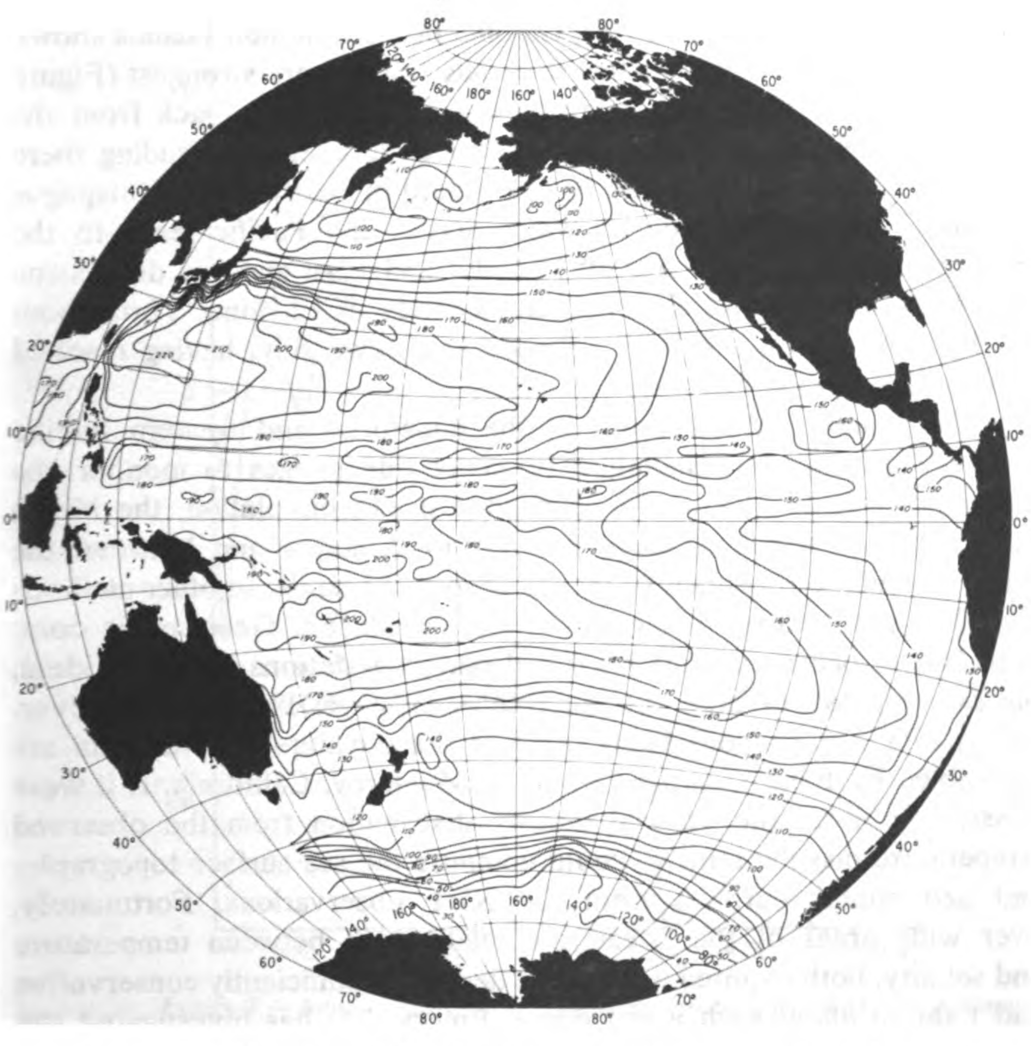


Figure 6 – Mean annual dynamic topography of the sea surface relative to 1000 db in dyn cm; 36,356 observations.

Pacific for the period 1950 to 1970 (12). By using the difference of sea level between Christmas Island, representing the equatorial ridge, and Kwajalein, representing the equatorial trough, as a measure of the strength of the equatorial countercurrent, it was shown that this current transports more water eastward during El Nino years than it normally does (13). The event, El Nino, is characterized by unusual temperature changes over large areas of the eastern tropical Pacific Ocean. These large-scale temperature anomalies in the upper ocean have been shown to be manifestations of changes in the ocean-atmosphere system over the entire Pacific Ocean and possibly over the entire globe. The unusual warming, referred to as El Nino, has dramatic consequences both on the coastal and offshore environs of Ecuador and Peru. More recently, the development of El Nino in 1972/73 was studied in relation to sea level. As explained by Wyrtki (14), a long period of very strong southeast trades in the Pacific preceded El Nino, leading to the accumulation of water in the region between Samoa and the Solomon Islands. Sea level as observed at Anewa Bay, Bougainville, in the Solomon Islands shows a peak in 1971 at the time when the trade winds were strongest (Figure 7). As soon as the trades relaxed, water was flowing back from the western Pacific along the equator to the eastern Pacific, leading there to a rise of sea level as shown by the record of Baltra in the Galapagos Islands. This backsloshing of water across the Pacific leads to the accumulation of warm water off Ecuador and Peru and to a depression of the thermocline, which are characteristics of El Nino. Throughout the El Nino event, sea level dropped at Anewa Bay, having reached a low in January 1973.

While islands are numerous in the equatorial and western Pacific Ocean, allowing the installation of many tide gauges to monitor the fluctuating sea level and the associated ocean circulation, the North Pacific Ocean between Japan and North America and between the Aleutian and the Hawaiian Islands is devoid of islands, so other methods have to be developed to monitor ocean circulation. Geostrophic computations of ocean currents from hydrographic stations would be ideal, but as previously pointed out, much too expensive. There are, however, many XBT observations being taken in these waters, and the data are assembled by Fleet Weather Central in Monterey, California. If it were possible to infer the vertical density distribution from the observed temperature distribution, we could compute the sea surface topography and geostrophic currents from the XBT observations. Fortunately, over wide areas of the ocean the relationship between temperature and salinity, both required to compute density, is sufficiently conservative and tight to allow such a procedure. Emery (15) has investigated the possibility of calculating dynamic heights from vertical profiles of temperature only, when the average temperature-salinity relationship

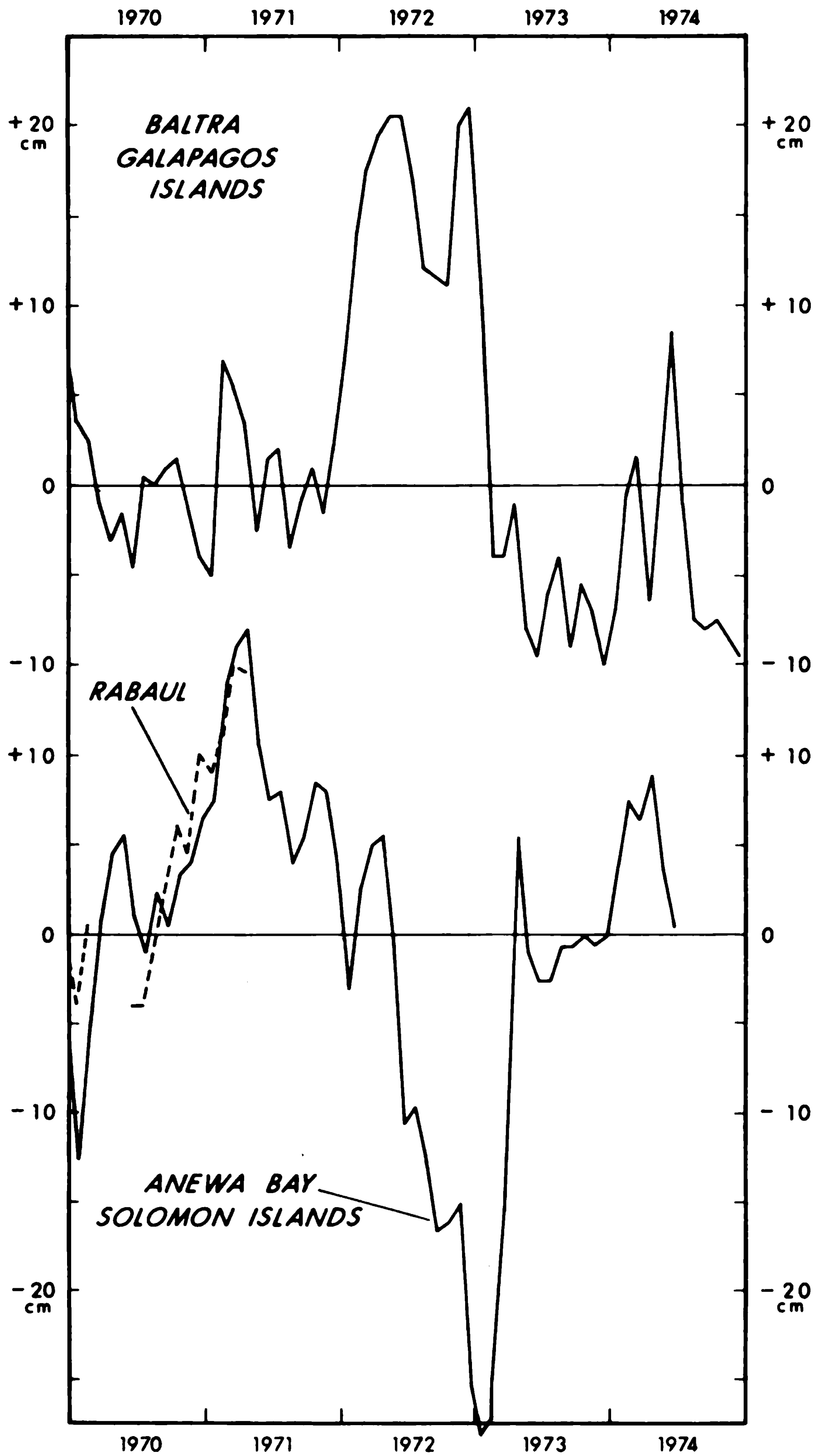


Figure 7 — Sea level at Baltra, Galapagos Islands; at Anews Bay, Solomon Islands and Rabaul during the 1972-73 El Nino event.

is known. He has found that over large parts of the ocean, in particular in the subtropical gyre and in the North Pacific Current, conditions are favorable for using average temperature-salinity relationships together with observed temperature profiles to compute dynamic heights. Consequently, we are in a position to use XBT observation as a substitute for hydrographic stations in making dynamic computations and inferring the geostrophic circulation. The application of this method to the study of the fluctuation of North Pacific circulation is presently under way.

The goal of using both the sea level observations and the XBT observations for dynamic computations is to determine the fluctuations of the topography of the sea surface and of the associated ocean circulation. Sea level observations and the slow fluctuations in thermal structure are the only oceanographic records that make the low frequency dynamics of the ocean accessible to us. Their use will provide a continuous monitoring of the circulation of the major ocean gyres and currents and will allow us to relate changes in ocean circulation to those in atmospheric circulation and to draw conclusions about the movements of large heat storage anomalies. The monitoring of ocean circulation also will enable us to test the predictions derived from numerical models with the aim to improve their performance.

For decades, meteorologists have used surface atmospheric pressure maps to monitor the changing atmospheric circulation. We are looking forward to the day when, for substantial areas of the oceans, similar charts of sea surface topography can be drawn, and oceanographers can look at the changing patterns of ocean circulation as meteorologists now look at atmospheric circulation. Our research is aimed in this direction.

Reference

1. J. Namias, *J. Geophys. Res.*, **64**, 631 (1959).
2. J. Namias, *J. Geophys. Res.* **70**, 2307 (1965).
3. J. Namias, Collected works of J. Namias, 1943 through 1974. Univer. of Calif., San Diego (1975).
4. W. B. White, *J. Mar. Res.*, **33**, 141 (1975).
5. W. B. White, NORPAX Highlights, **3**, 2 (1975).
6. F. Favorite and D. McLain, Nature, **244**, 139 (1973).
7. R. L. Bernstein and W. B. White, *J. Phys. Oceanogr.*, **4**, 613 (1974).
8. W. B. White, NORPAX Highlights, **3**, 2 (1975).
9. G. Dietrich, Gebruder Borntraeger, Berlin (1957).
10. K. Wyrtki, NAGA Report, **2**, Univ. of Calif. (1961).
11. K. Wyrtki, *J. Phys. Oceanogr.*, **5**, 450 (1975).
12. K. Wyrtki, *J. Phys. Oceanogr.*, **4**, 372 (1974).
13. K. Wyrtki, *Science*, **180**, 66, (1973).
14. K. Wyrtki, *J. Phys. Oceanogr.*, **5**, 572 (1975).
15. W. J. Emery, *J. Phys. Oceanogr.*, **5**, 369 (1975).

Studies of the Monsoon Region of the Indian Ocean

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The Indian Ocean is rapidly becoming a high priority region for Navy missions. Our knowledge of it's oceanography is extremely limited compared to the North Atlantic and the North Pacific. The Office of Naval Research is jointly sponsoring with the National Science Foundation the investigation described in this article. The investment in basic research dollars is minimal; however, a handful of physical oceanographers are discovering new and exciting facts about the Indian Ocean. This is accomplished using Fleet ships, oil tankers, small charter boats, British facilities at Gan, a Norwegian fisheries research vessel, and the R. V. Atlantis II from Woods Hole. The initial results of the project are interesting and are shared with the readers of Naval Research Reviews.

Purpose and Objectives

An oceanographic research program called INDEX is underway in the Indian Ocean. INDEX is a pilot study to obtain data to aid in planning the oceanographic component for MONEX/FGGE.†

The purpose of the INDEX and MONEX oceanographic experiments is to explore the ocean's complex interactive role with the Indian summer monsoon. The U.S. oceanographic community is sharing this task cooperatively with oceanographers of other nations. The main scientific objective is to understand the time-dependent response of the Indian Ocean to the variable wind forcing due to the monsoons, and the nature of the feedback which the ocean produces on the monsoon regime itself.

The opportunity of making a major oceanographic contribution in this region and at this time is particularly auspicious, for the following reasons:

1. *The amplitude of wind forcing and ocean response is large.* The Indian Ocean monsoon is the strongest large-scale, long-period variable forcing that the atmosphere exerts upon the ocean, and the variability of its major currents (e.g., the Somali Current) is the most pronounced

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†MONEX: Monsoon Experiment; FGGE: First GARP (Global Atmospheric Research Program) Global Experiment.

in the world. Such large amplitude makes measurement easier; the signal is larger than the noise.

2. *The ocean affects the climate.* Evidence is accumulating that links sea-surface temperature anomalies with the anomalies in rainfall over India. The documentation of variability of sea-surface temperature over the Arabian Sea (5) has been linked (1) to records of rainfall over India by a correlation analysis of data from 1900-1960. Shukla (2) has shown that, by inserting anomalous Arabian Sea temperatures into the Princeton Geophysical Fluid Dynamics Laboratory (GFDL) General Circulation Model, higher sea temperatures lead causally to higher precipition over India. Also, other types of linkage have been exposed between the intensity of the East African low-level jet and Indian rainfall (3-4), and between the time of onset of the monsoon over the Arabian Sea and June rainfall (5).

3. *It will be a time of especially good meteorological coverage which can be studied simultaneously with the interpretation of the ocean variability.*

4. *A substantial interest on the part of oceanographers has grown out of their involvement in International Indian Ocean Expedition (IIOE) (1960-65).* This includes many recent attempts at analytical and numerical modelling of the response of the Indian Ocean to the monsoons, and a series of observational studies (e.g., Knox's 2-1/2-year monitoring of the vertical current profile at the equator at Gan) aimed at documenting the variability of the current regime. The various field programs are being stepped up and coordinated as pilot programs for the INDEX effort during FGGE.

5. *An opportunity for specific joint meteorological-oceanographic field studies exists.* Joint field studies using research aircraft and vessels are being projected for the East African Jet and Somali Current Region and in the Bay of Bengal. These programs will provide an opportunity for meteorologists and oceanographers to learn to work together on joint problems.

Regional Studies in the Indian Ocean

Any study of the effect of the monsoon on the Western Indian Ocean necessarily will be composed of a number of regional experiments. Of course these studies are inherently interesting to oceanographers, and the opportunity of enhanced meteorological coverage during FGGE makes this an attractive time to pursue them. The Somali Current is a reversing western boundary current, and the Equatorial Current System is an extreme example of equatorial variability. In order to interest physical oceanographers, and to draw upon their observational resources, the formulation of the oceanographic program for MONEX must contain elements that involve the study of a variety of oceanic dynamical processes.

The justification for regional studies is more direct than that. Certainly both the Somali Current and the Arabian upwelling contribute to the overall cooling of the western Arabian Sea, and thus they play an important part in the ocean-atmosphere feedback mechanism that controls the monsoon. The dynamic of the Equatorial Current System is a key mechanism to understanding whether good low-latitude ocean circulation models are to be constructed and run coupled with atmospheric general circulation models. The monsoonal variability of the Equatorial Current System in the Indian Ocean makes it unique for testing dynamical models and hence gives it an importance that transcends the Indian Ocean alone.

Figures 1-4 show the programs scheduled for 1975 through MONEX, 1979. The pilot studies are summarized in Table 1.

The specific scientific objectives of the Equatorial Region are:

1. To obtain an expanded time and space coverage of the undercurrent.
2. To look for time-dependent motions in the surface and undercurrents.
3. To examine the time and space scales in the deep water.

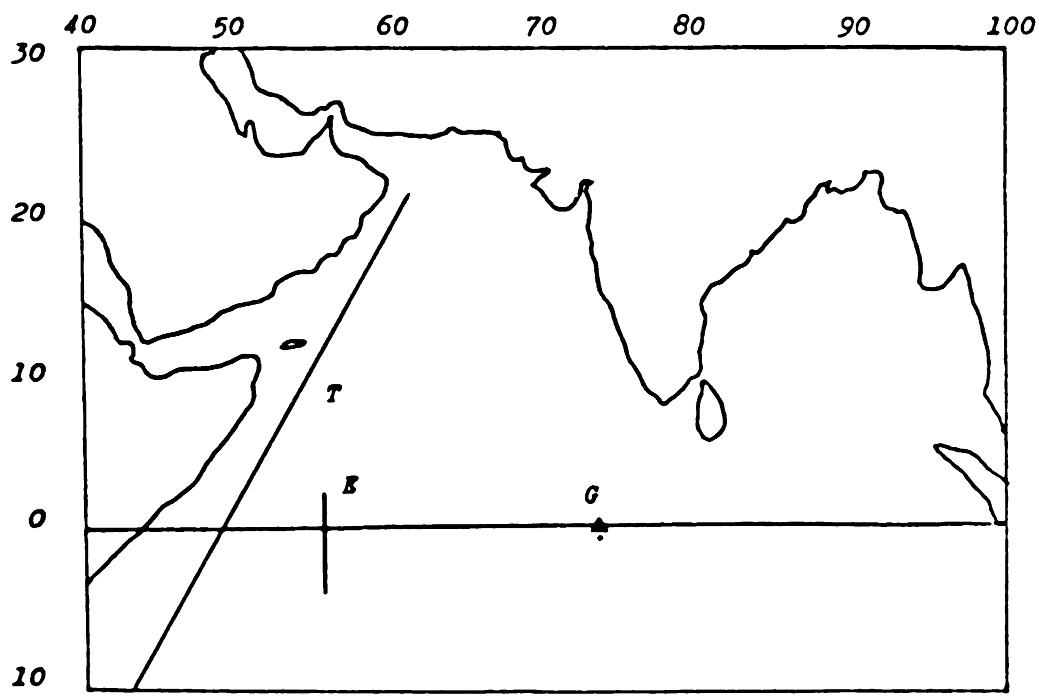

Figure 1 — 1975 INDEX Program

T Tankers taking XBTs

G Gan Is. Velocity Profiles (1973-75)

E Equatorial Velocity Profile Section

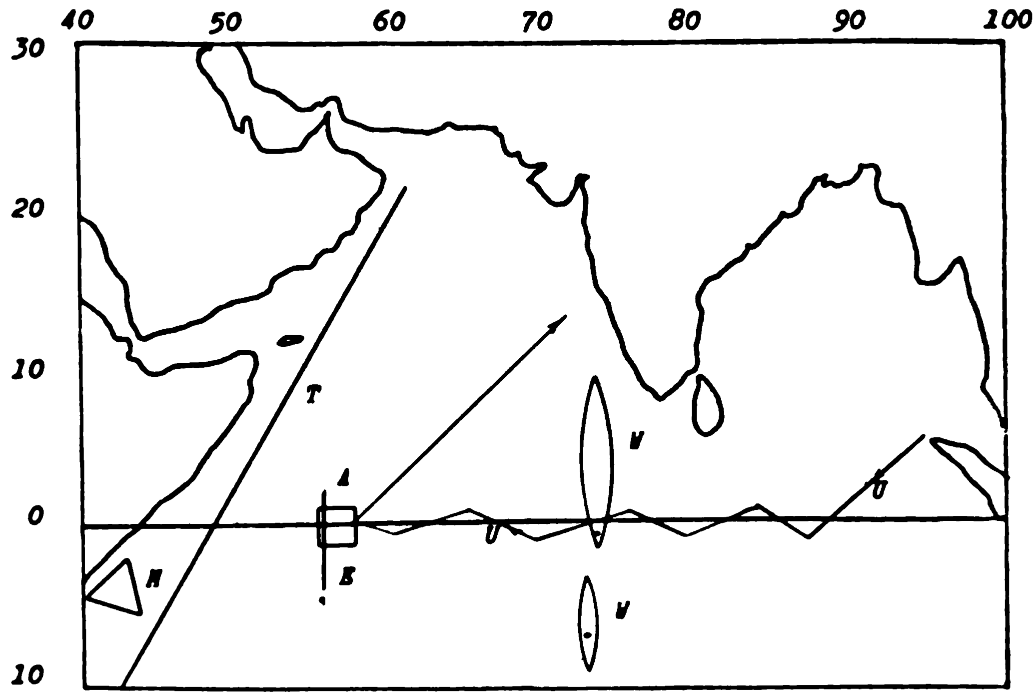

Figure 2 — 1976 INDEX Program

T Tankers taking XBTs
E Equatorial Velocity Profile Section
M Current meter moorings
A Equatorial moored arrays
W Equatorial sea-level arrays
U Atlantis II underway survey

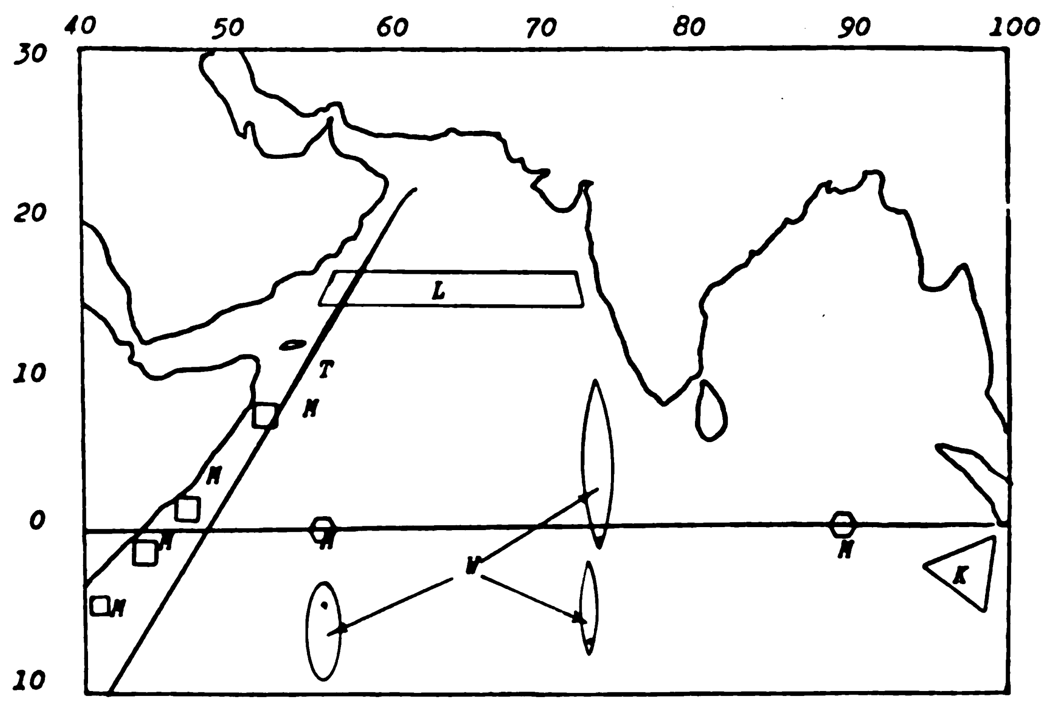

Figure 3 — Proposed 1977 INDEX Program

T Tankers taking XBTs
M Current meter moorings
W Equatorial sea-level arrays
L Mixed layer survey
K Kelvin-wave survey

in addition to the USSR-India Program MONSOON-77

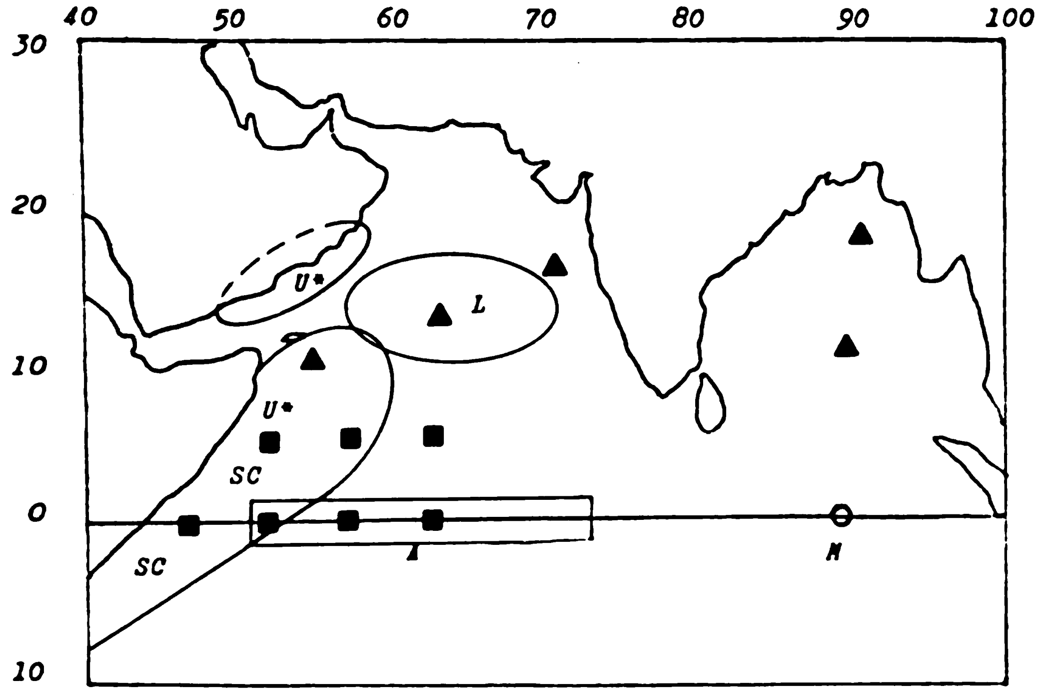

Figure 4 — Tentative MONEX 1979 Program

■ *FGGE Meteorological Ships*
▲ *Monex Ships*
L Layer Study
Proposed INDEX 1978-1979 Program
U Upwelling study*
A Equatorial array
SC Somali Current Study
M Moored current meter

4. To correlate changes in the equatorial regions with those along the Somali coast.
5. To advance numerical modelling as an interpretive and predictive tool for understanding the Indian Ocean circulation.
6. To attempt identification of vertical and latitudinal modal structure.
7. To test the theory of propagation of equatorial waves against observed dispersion relationship.
8. To determine phase relationships of the response time of various parts of the equatorial system.
9. To attempt to determine the importance of upwelling and non-linear effects.
10. To study inertio-gravitational equatorial modes.

Objectives 1 through 4 and 10 appear to be reasonable goals for pilot field studies during 1975-76. Objectives 5 through 9 will require a somewhat expanded field program during FGGE.

Field Studies

A pilot study in the equatorial region was begun in mid-January 1975 and will run through 1976. The objectives of the study are

TABLE 1 — INDEX REGIONAL PILOT STUDIES

REGION I: EQUATOR

INVESTIGATORS	VESSEL	LOCATION	OBSERVATIONS	FREQUENCY	DURATION
R. Knox, SIO	(R.A.F.)	Gan Island: 73°E, 0°30'S	Current velocity profiles; temperature soundings to 300 m	weekly	Jan. 1973--mid-1975
	La Curieuse	Seychelles Bank: 54°41'E, 0°1'N	2 moorings, 1 current meter each, at 500 m	bi-monthly, renew at 2-month intervals	Feb. 1976--late 1977
H. Stommel, MIT A. Leetmaa, AOML	La Curieuse	3°S-2°N, along 55°E (N of Seychelles)	Velocity and temperature profiles, surface to 300 m	Approx. bi-weekly	mid-Feb.--late May 1975
	La Curieuse	3°S-2°N along 55°E	Velocity and temperature profiles, surface to 500 m; satellite-tracked drifters	Approx. bi-weekly, modified for better resolution	Jan--June 1976
J. Luyten, WHOI C. Wunsch, MIT	Atlantis II	50°30'E, 53°E, 57°E at 0°; 53°E at 1°20'N	Current meter moorings, VACM's at 500 m, 1500 m, 4000 m; T/P recorder at 800 m	---	May 1976--Jan. 1977
	Atlantis II	53°E, 1°45'N	Small-scale bottom array; 3 moorings, 5 km apart	---	May 1976--Jan. 1977
J. Luyten, WHOI W. Duing, Miami	Atlantis II	53°E, at 0°45'S, 0°, 0°45'N, 1°30'N, 3°N, 5°N	Equatorial current profiles: White Horse acoustic profiler, surface to bottom; profiling c.m., surface to 400 m	weekly	May--June 1976 (30 days)
C. Wunsch, MIT	---	Maldive Is. (3 locations), Seychelles (2 locations), Diego Garcia (1 location)	8 tide gauges: sea level, from self-contained pressure gauge	---	May--Dec. 1976

TABLE 1 — INDEX REGIONAL PILOT STUDIES (continued)

REGION II: SOMALI CURRENT

INVESTIGATORS	VESSEL	LOCATION	OBSERVATIONS	FREQUENCY	DURATION
W. Duing, Miami F. Schott, Kiel	R/V Hansen	South of equator off Kenya Planned off Somalia	4 moorings and 3 subsurface T/P recorders	--- ---	Jan.--Aug. 1976 1977
J. Bruce, WHOI	Exxon tankers	Track parallel to Somali coast, 200 mi. offshore (22^oN to 2^oS)	XBT's	bi-weekly	Oct. 1975 thru 1976

REGION III: UPWELLING, ARABIAN SEA

NO PILOT FIELD PROGRAM IN THE ARABIAN SEA; CUEA STUDIES COULD BE CONSIDERED A PILOT EXPERIMENT.

REGION IV: REMOTE SENSING, INTERIOR OF ARABIAN SEA

INVESTIGATORS	EQUIPMENT	LOCATION	OBSERVATIONS	FREQUENCY	DURATION
W. Duing, Miami O. Brown, Miami	NOAA/NESS DMSP; NIMBUS F satellite	Somali Current region and interior of Arabian Sea	Sea-surface temperature	---	1976--1977
H. Stommel, MIT N.I.O., Goa	---	Goa--Socotra	Hydrographic sections (preliminary discussions underway)	3-week intervals	May--Aug. 1977

1. To extend the time series of current measurements carried out at Gan to another equatorial location.

2. To begin regular velocity profile sections across the equator using a locally chartered vessel.

A typical pilot study for the equatorial region is the program carried out by Prof. Henry Stommel, of M.I.T., and Dr. Ants Leetmaa, of NOAA's Atlantic and Meteorological Laboratory (AOML). A 68-foot schooner, La Curieuse, was chartered in the Seychelles from mid-January to mid-June 1975. Velocity and temperature profiles were run from 3°S to 2°N. From mid-February to late May a total of eight sections were made. The preliminary data analysis has begun. To illustrate the salient features that were observed, the relative velocity at 10 m, at the level of the core of the undercurrent, and the average velocity from 250 m to the bottom of the profile are shown for each section in Figure 5. As can be seen, a strong undercurrent with maximum speeds in the core of 70-100 cm/sec was observed during February-April. This undercurrent meandered back and forth across the equator within a period of the order of 20 days. This estimate of the period is possibly aliased, however, because it is comparable to twice our sampling frequency. During May the surface layers also begin to flow toward the east, so during this time period an eastward jet, in and above the thermocline, is difficult to distinguish from the undercurrent which was previously present.

During 1976 the same vessel will be chartered. A program similar to that of 1975 will be better resolved. More effort will go into determining the absolute velocities for the profiles, which will be carried

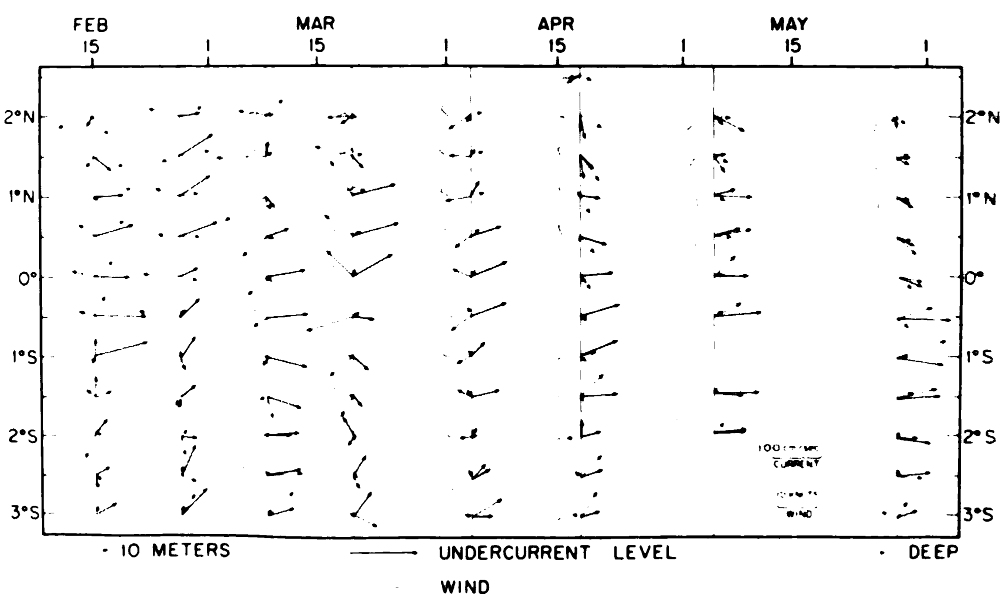

Figure 5 — Velocities and Winds

deeper (500 m vs. 300 m in 1975). During this time satellite-tracked drifters will be launched into the undercurrent to see whether the horizontal meandering can be deduced from their tracks. The necessary channels have been obtained on TWERLE/RAMS (Nimbus F). During May and June the charter vessel will work in conjunction with *Atlantis II* in order to obtain expanded longitudinal coverage along the equator.

Another INDEX project is a study by Mr. John Bruce, of Woods Hole Oceanographic Institution, on the temperature field off the Somali and Arabian coasts using XBT's from Exxon tankers. Bruce already has data from 4 sections, taken in October and November of 1975 and January and February of 1976. A striking example of the kind of information that can be obtained using XBT's is provided by the 4-ship survey conducted by the U.S. Navy on August 11 and 12, 1975. The United States ships *Reeves, Badger, Holt,* and *Mispillion* steamed on parallel courses along the Somali coast, taking frequent XBT's to 450 meters. The data has been worked up by Bruce, who has provided Figure 6, showing the temperature field at 100 meters during this survey. The very cold water (< 13°C.) near 9°N is associated with the upwelling near the separation point of the Somali Current. The tanker tracks are farther offshore, but they provide the same general information about the position of the separted Somali Current.

A final example of the kind of data being taken in the INDEX program is provided by the time series from morred current meters collected by Dr. Walter Duing, of the University of Miami, off the Somali coast, from August 1975 through January 1976. Stick diagrams of the 12-hour averaged currents are shown in Figure 7. The winds at Mogadiscio are included for comparison. The strong southerly flow at all depths from early September through mid-October shows no relationship to the local wind forcing and is not as yet explained. The winds at Mogadiscio clearly show the switch from SW to NE Monsoon in mid-November, and the current flow also is predominantly southward from then on.

Other Studies and Future Plans

In addition to the field program described above, there is a significant theoretical modelling effort, involving both analytical and numerical models. Models have been or are being developed to study each of the major features of the circulation in the INDEX area. We are planning a major workshop in the summer of 1977 to evaluate and extend the model studies, especially in light of the pilot data taken in 1975 and 1976. The aim of this workshop is to help with the detailed design of the oceanographic field program to be conducted under MONEX auspices during the First GARP Global Experiment.

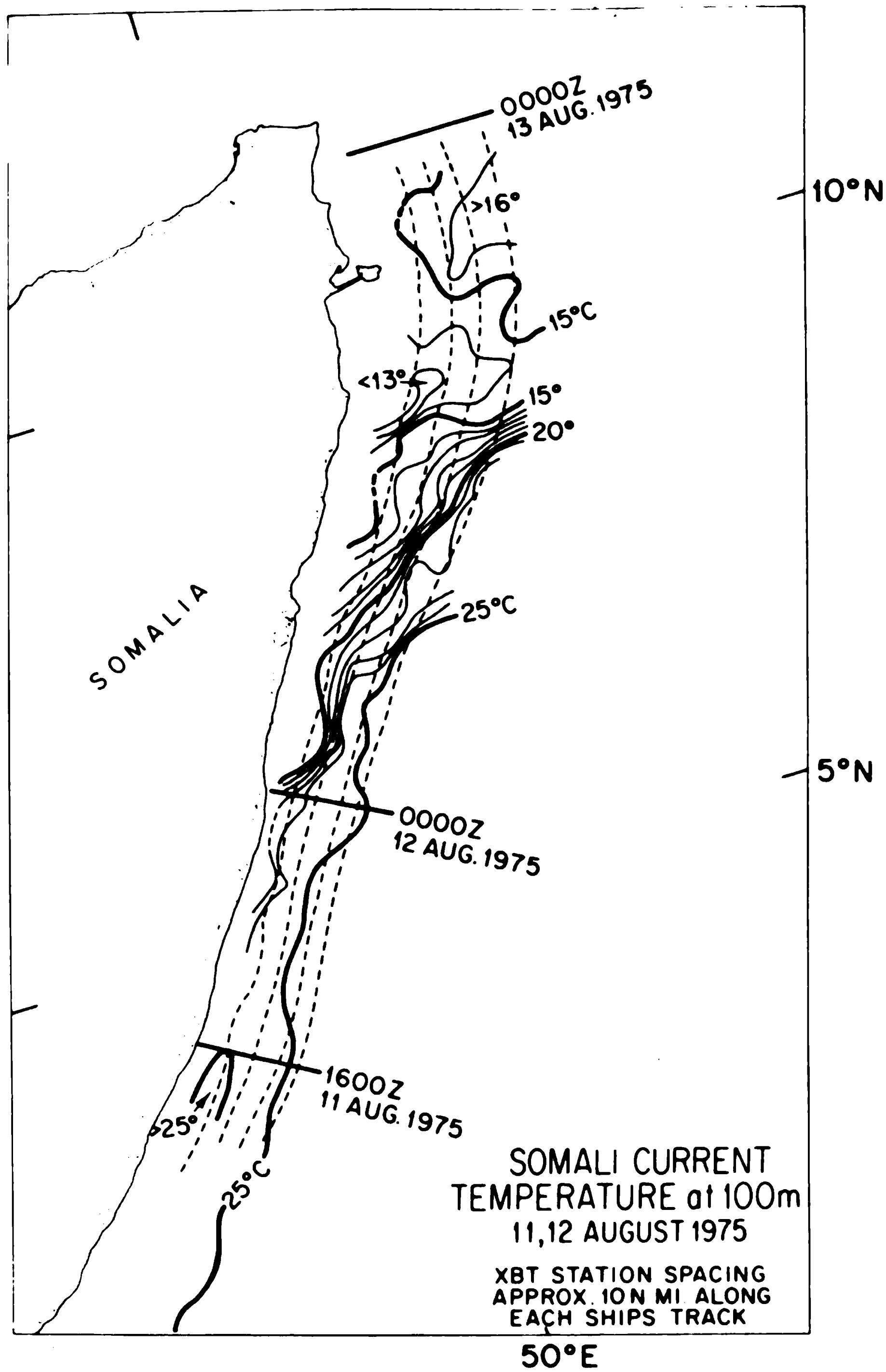

Figure 6 – Map of temperature (0°C.) at 100 m depth in the Samali Current during August 11 and 12, 1975, drawn from XBT sections from USS REEVES (CG 24), USS BADGER (FF 1071), USS HOLT (FF 1074), and USNS MISPILLION (TAO 105). Ships' tracks shown as dashed lines. During survey ships maintained radar range (12-20 n.m.) and bearing on one another and on the coast. XBT probes were type T-4, 450 m maximum depth.

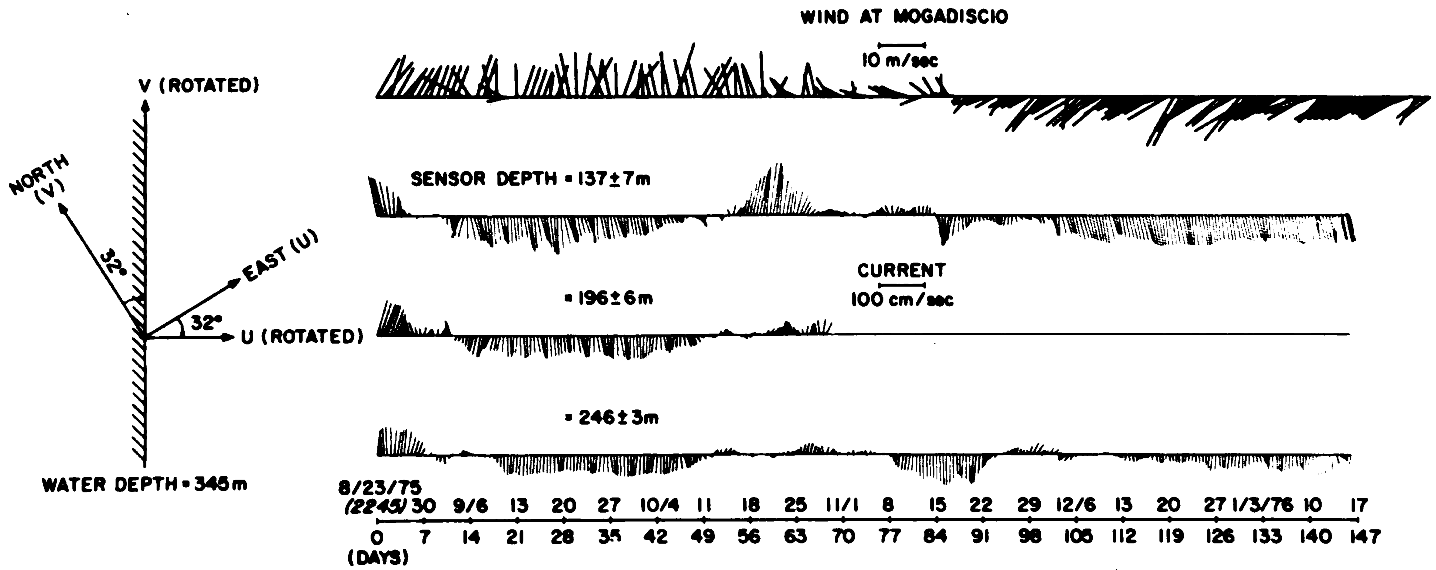

Figure 7 — 5-month-long records for wind and current off the Somali Coast. Wind vectors are instantaneous values observed at 12 GMT; current vectors are averaged over 12 hours. The wind at Mogadiscio shows the reversal from SW Monsoon to NE Monsoon to occur in mid-November. Surprisingly, the currents do not show such a simple pattern. The reason for the (quasi-barotropic) flow toward SW from early September to mid-October is presently unclear. (Provided by W. Duing, University of Miami.)

References

1. J. Shukla and B. M. Misra, 1976: Time correlation between sea surface temperature and wind speed over the Arabian Sea and monsoon rainfall over India (in preparation).
2. J. Shukla, 1975: "Effect of Arabian Sea-Surface Temperature Anomaly on Indian Summer Monsoon: A numerical Experiment with the GFDL Model." *J. Atmos. Sci.*, **32**, 503-511.
3. J. Findlater, 1969: "A Major Low-Level Air Current Near the Indian Ocean During the Northern Summer." *Quart. J. Met. Soc.*, **95**, 362-380.
4. K. Saha, 1974: "Some Aspects of the Arabian Sea Summer Monsoon." *Tellus*, **26**, 464-476.
5. M. Fieux, 1975: "Establishment de la Monsson de Sud Ouest an Mar D'Arabie: Structure Spaciale et Temparelle." *Comp. de Rendes a la Academie de Science*, Oct. 20.

Satellite-Tracked Drifters Give Data on Gulf Stream

In July 1975, scientists from Texas A&M University and Scripps Institution of Oceanography, sailing aboard the USS Preserver (ARS-8), deployed a set of drifting buoys in the Gulf Stream east of Florida. The deployment has a twofold purpose. First, it was a test of the Random Access Measurement System (RAMS) aboard the Nimbus 6 satellite as a means of tracking drifting buoys and thereby determining the details of ocean currents. The second purpose was to obtain observations of the Gulf Stream from Florida north toward the open Atlantic Ocean.

Dr. A. D. Kirwan, Texas A&M University, and Gerard McNally, Scripps, have reported that the experiment was completely successful. The position error of the buoys was well within the design limits of 5 km. Although this position introduced some error in determining velocity and acceleration in the current, appropriate averaging reduced these to no greater than 4 cm/sec. To account for errors in velocity that might be introduced by winds, the surface wind field produced by Fleet Numerical Weather Central was used. As it turned out, any wind speeds less than 10 knots had no influence on the velocity of the drifters in the Gulf Stream.

From 20 to 26 July, the one drifter that had not been recovered was following a path along the eastern seaboard south of Cape Hatteras. At that point, the drifter turned east into that part of the Gulf Stream where meanders are usually observed. The trajectory showed that the meanders were indeed active in July 1975. From 26 July through 25 September the drifter followed a complicated meandering path that included a 20-day period when it was caught in an anticyclonic eddy centered at 38.5°N, 47°W. It was clear, therefore, that the drifter closely followed the Gulf Stream eddies' meanders whose existence have been well documented in the past.

(Continued on inside back cover)

Gulf Stream Cyclonic Rings

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and

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Woods Hole Oceanographic Institution

Gulf Stream Rings

The physical structure and dynamic evolution of cyclonic rings generated by the Gulf Stream is a subject of active research by a group of Navy-sponsored scientists. The origin of our knowledge of these mesoscale oceanic features can be easily traced to pioneer work by Columbus Iselin at Woods Hole Oceanographic Institution (WHOI) in 1936 (1). Iselin's work showed that rings (then referred to as eddies) existed as large, vertical perturbations of the main thermocline in the Sargasso Sea (Figure 1). A cyclonic ring appears as a dome of cold water in a temperature section along a diameter. A cold central region corresponds to a mass of North American Slope Water which is trapped as a deep cyclonic meander of the Gulf Stream separates from the main flow. The region of large temperature gradient surrounding the cold core is indicative of an encircling remnant or "ring" of the Stream. The area of the core can be approximated as that of a one-degree square at mid-latitudes, although the overall size is considerably larger. The generation and evolution of a ring was first examined during a series of cruises conducted from WHOI in 1951 (2). The first data on the longevity and evolution of the spatial structure of a ring was determined during 1967 by following a single cyclonic ring for a nine-month period. A study of the potential energy distribution as a function of time yielded a projected three to five year lifetime for this ring (3). The implications of the data became clear; cyclonic rings were the most energetic of ocean eddies. They provide a dynamic means for the shedding of cyclonic vorticity by the parent Gulf Stream, and they provided a mechanism for altering the physical structure of the Sargasso Sea.

*Dr. Andrew Vastano is an Associate Professor of Oceanography at Texas A&M University. His fields of research include tsunamis, storm surges, influence of seamounts on oceanic flow and Gulf Stream rings. Dr. Philip Richardson, recently from the University of Rhode Island, focuses his research on the climatology and dynamics of Gulf Stream rings. He is now at Woods Hole Oceanographic Institution.

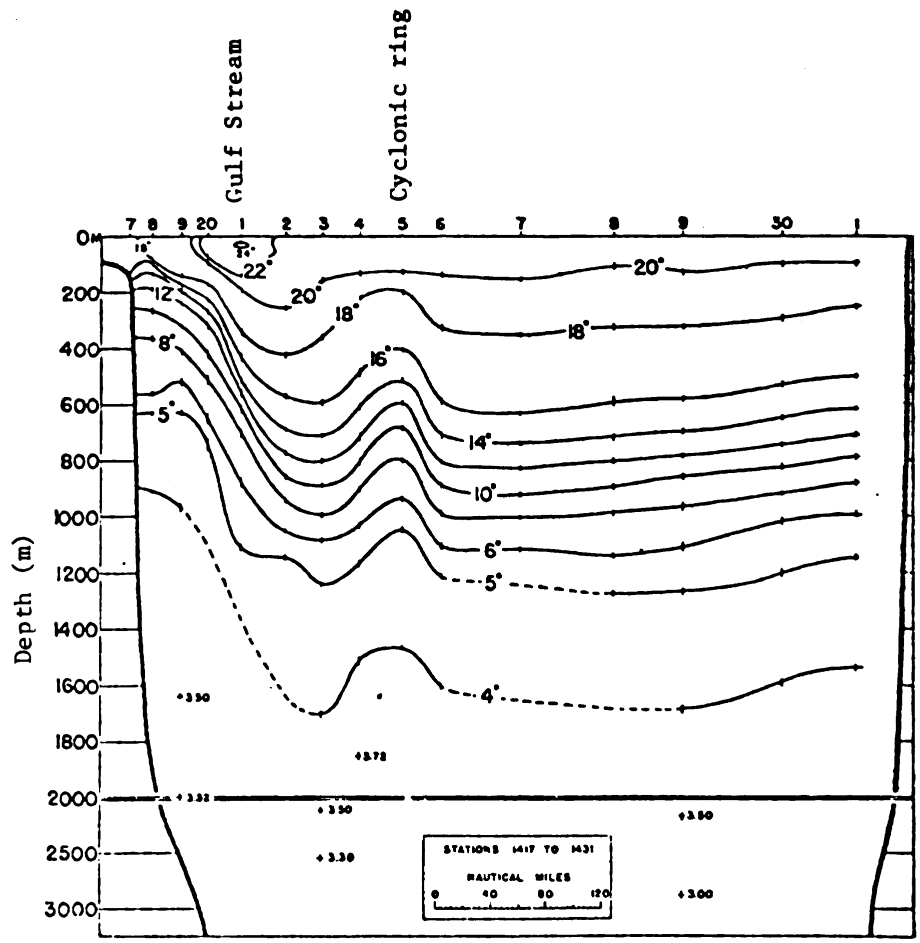

Figure 1 — Temperature section showing a cyclonic ring (Iselin, 1936).

The distribution and number of cyclonic rings in the Sargasso Sea is important as an indication of their potential effect on the Gulf Stream system and on the dynamics and physical structure of the Sargasso Sea. The results of a survey of the Bathythermograph (BT) file at WHOI detailed a number of actual sightings of rings, either intentional or by chance, during the period 1932 to 1970 (4). The distribution, shown in Figure 2, indicates a western ring region curiously separated from a possible eastern ring region by an area possessing no rings. However, an analysis of data since 1970 and several cruises during the last year to the region between 50-60°W have indicated that rings are found there, although their near surface expression is reduced from that of the western region (5). The discovery of several large rings, roughly 200 km in diameter, and a meander sufficiently large to form them indicates rings form in this region as well as the western area. The analyses of historical data plus the repeated observations of a few rings suggest that on the average they move in the west and southwest

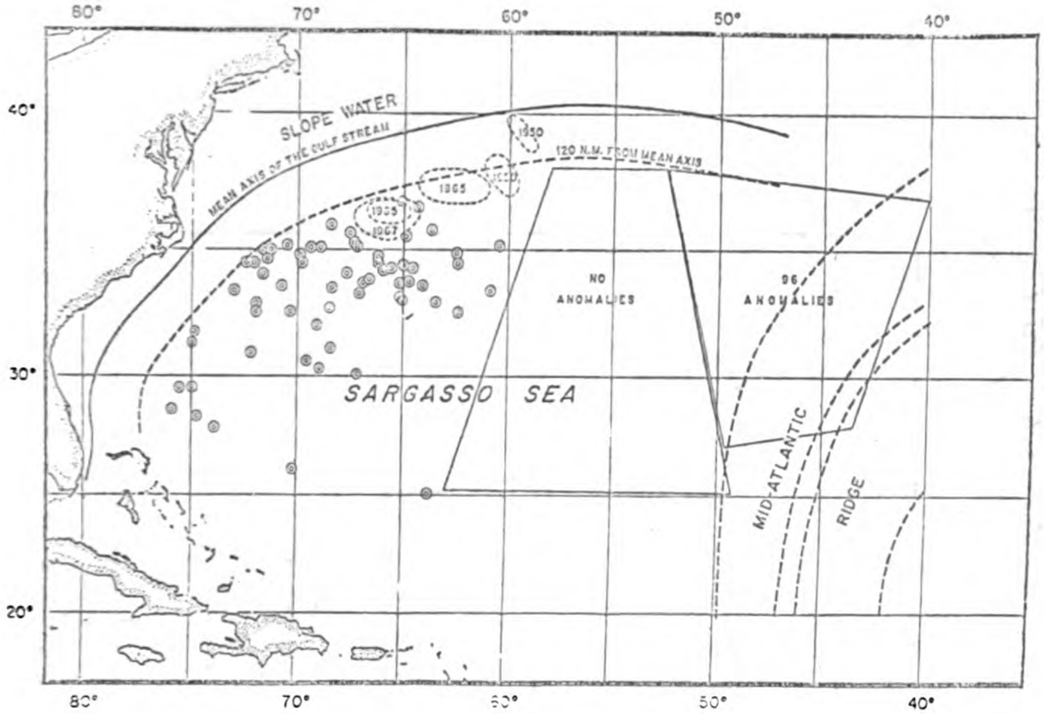

Figure 2 — Observations of rings 1932-1970 (Parker, 1971)

directions. A fourteen month survey of a ring indicated it moved from east of Cape Hatteras southwest and parallel to the average Gulf Stream path to the Blake Plateau off Florida where the ring was thought to have coalesced with the Gulf Stream (6). The observed westward component of ring movement is in agreement with the theoretical analysis given by B. A. Warren (7) and, also, with the mean currents in the Sargasso Sea.

The physical structure of cyclonic rings varies during the ring lifetime as the ring slowly decays. Surface velocity and serial temperature and salinity observations have shown a horizontal shrinking and shrinking of the thermocline in rings. The decay of a ring is shown in Figure 3 (8). Changes in the oxygen and temperature distribution have been examined and a tentative picture of the radial movement of water has been developed utilizing field observations (Figure 4) (9,10). A numerical study of the spin-down process was carried out which predicted a longevity for the 1967 ring that was roughly half that given by Barrett and more in accord with later data (11). Recent work has shown analytically that the horizontal flow pattern in a cyclonic ring varies with depth and that a region in the upper water is carried along with the ring as it moves through the ocean and that deeper water can pass through the ring (12). Subsurface floats set by NAVOCEANO and WHOI in a cyclonic ring support this picture. A long range acoustic

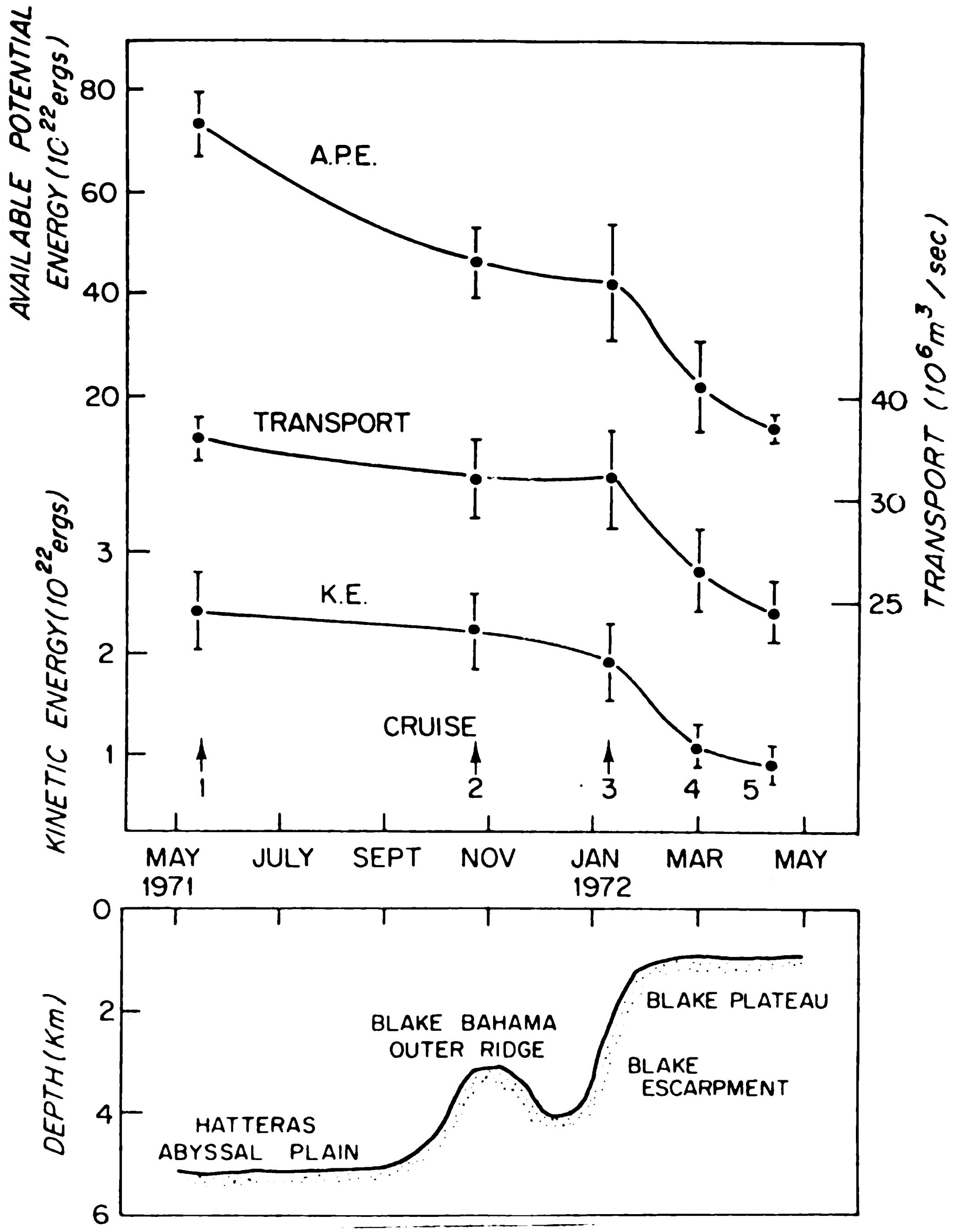

Figure 3 — Decay of available potential energy, transport, and kinetic energy relative to 1000 m. Variation of depth under the center of the ring is shown below. (Cheney and Richardson, 1975)

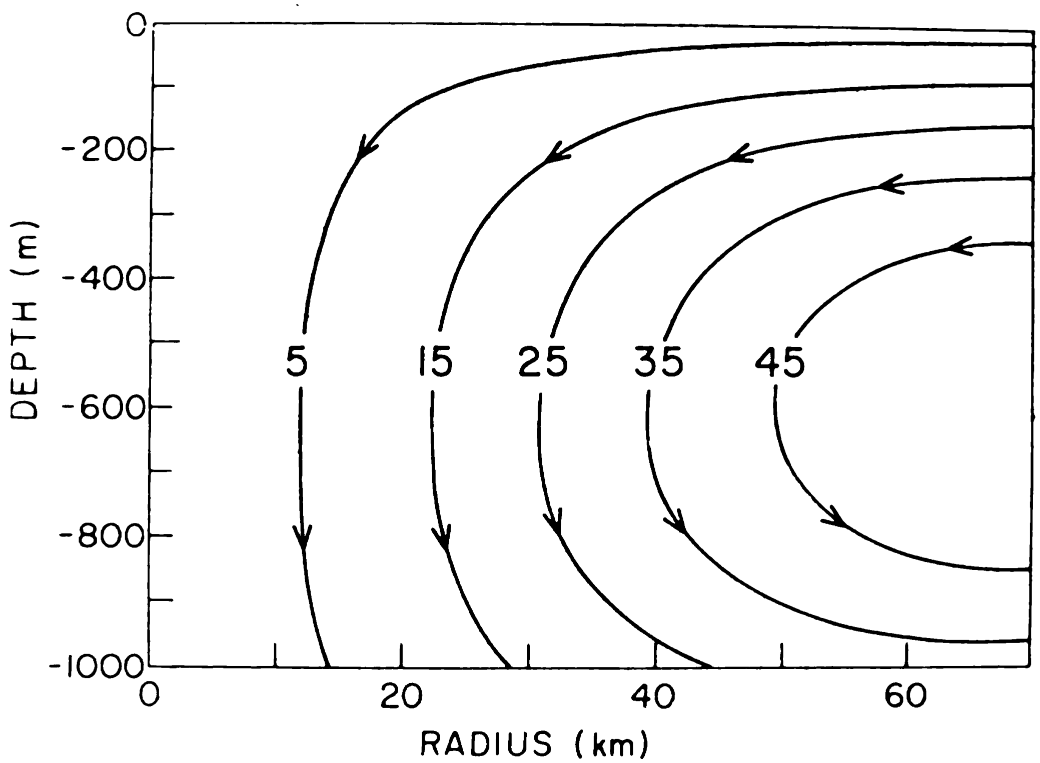

Figure 4 — Field of streamlines (10^8 cm^3/sec^{-1} rad^{-1}) (Schmitz and Vastano, 1975). Maximum vertical speed at the center is 10^{-3}cm/sec and maximum radial speeds are approximately 10^{-2}cm/sec.

effect of cyclonic rings has been theoretically demonstrated (13). The low sound velocity region in the core of the 1967 ring was studied with ray trace techniques and showed a pronounced tendency to focus shallow water sound energy at lower depths, outside the ring, on the Sargasso Sea sound channel axis.

Research Goals

The analysis of data on file at NODC and Fleet Numerical Weather Facility suggest that at least ten rings are present at a given time. Although satellite measurements provide intermittent views of the surface temperature field and are valuable in occasionally identifying rings from their generation time to an age of a few months, it is quite probable that the majority of rings present in the Sargasso Sea will be found by deep temperature measurements by ship survey. A census over the entire region and subsequent tracking of rings found will provide data permitting a logical attack on problems of origins and alternative fates of cyclonic rings. As yet, a complete quasi-synoptic survey has not been carried out and is a primary goal of present research.

The aging process in a cyclonic ring has been numerically modelled with limited success. The current area of investigation centers on the acquisition of serial field measurements in a single ring with the goal of defining the dependence of critical coefficients in the governing equations of motion. In addition, several researchers are focusing on the idea that rings provide *in-situ* laboratories for investigating a number of biological and chemical problems. A ring provides a traceable water mass and represents a microcosm of the ocean. By understanding how a ring evolves, we will understand more about the ocean in general.

References

1. C. O'D. Iselin, 1936: A study of the circulation of the western North Atlantic. *Papers in Physical Oceanography and Meteorology*, Vol. IV, No. 4, 101 pp.
2. F. C. Fuglister and L. V. Worthington, 1951: Some results of a multiple ship survey of the Gulf Stream. *Tellus*, Vol. 3, No. 1, pp. 1-14.
3. J. R. Barrett, 1971: Available potential energy of Gulf Stream rings. *Deep-Sea Research*, Vol. 18, pp. 1221-1231.
4. C. E. Parker, 1971: Gulf Stream rings in the Sargasso Sea. *Deep-Sea Research*. Vol. 18, pp. 981-993.
5. D. Y. Lai and P. L. Richardson, 1975: Distribution and movement of Gulf Stream rings from historical data. *Trans. Am. Geophys. Un.*, Vol. 56, p. 379 (abstract).
6. P. L. Richardson, A. E. Strong and J. A. Knauss, 1973: Gulf Stream eddies: Recent observations in the western Sargasso Sea. *Journal of Physical Oceanography*, Vol. 3, No. 3, pp. 297-301.
7. B. A. Warren, 1967: Notes on translatory movement of rings of current with application to Gulf Stream eddies. *Deep-Sea Research*, Vol. 14, pp. 505-514.
8. R. E. Cheney and P. L. Richardson, 1976: Observed decay of a cyclonic Gulf Stream ring. *Deep-Sea Research*, in press.
9. Richard B. Lambert, Jr., 1974: Small-scale dissolved oxygen variations and the dynamics of Gulf Stream eddies. *Deep-Sea Research*, Vol. 21, pp. 529-546.
10. J. E. Schmitz and A. C. Vastano, 1975: Entrainment and diffusion in a Gulf Stream cyclonic ring. *Journal of Physical Oceanography*, Vol. 5, No. 1, pp. 93-97.
11. R. L. Molinari, 1970: Cyclonic ring spin-down in the North Atlantic. Ph.D. dissertation, Texas A&M University.
12. G. Flierl, 1975: Gulf Stream meandering, ring formation and ring propagation. Ph.D. dissertation, Harvard University.
13. A. C. Vastano and G. E. Owens, 1973: On the acoustic characteristics of a Gulf Stream cyclonic ring. *Journal of Physical Oceanography*, Vol. 3, No. 4, pp. 470-478.

(Continued from page 30)

The maximum current was, surprisingly, eastward of Cape Hatteras rather than south in what is normally considered the core of the Gulf Stream. Whereas south of the Cape, velocities were typically about 2 m/sec, to the east to about 67°W, they were in excess of 2.5 m/sec. Velocities of 1 m/sec or greater were recorded as far east as 55°W.

The results of the experiment demonstrated that (1) a drifter can follow the core of a current for extended periods of time, (2) the position-fixing system works well remotely for long periods, (3) the data return is in near real-time, and (4) current dynamics can be calculated from the data.

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IN THIS ISSUE

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Cover Caption

A drawing of the formation and movement of Gulf Stream cyclonic rings. Cyclonic eddies constructed of a cold core of slope water surrounded by an outer Gulf Stream ring are called cold eddies or rings while their anticyclonic counterparts are called warm eddies.

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