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PHYSICAL OCEANOGRAPHY PROGRAM

(ONR CODE 481/NORDA CODE 410)

REPORT FOR FY 77-78

1 June 1978

Ocean Science and Technology Division

Office of Naval Research

NSTL Station, Mississippi 39529

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PHYSICAL OCEANOGRAPHY PROGRAM.

(ONR Code 481/NORDA Code 410)

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REPORT FOR FY 1977-78 1978,

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SECTION I--INTRODUCTION

The Physical Oceanography Program (Code 481) of ONR's Ocean Science & Technology Division funds the bulk of the Navy's basic research program in physical oceanography. Code 481's FY 77 funding was $7½ million, FY 78 was $8¼ million, and FY 79 is anticipated to be at least $8½ million. This report presents a compilation of those research efforts currently funded by Code 481.

The objective of the Physical Oceanography Program is to improve our understanding of those open-ocean physical processes which are of fundamental scientific importance and which impact on present or potential Naval operations. It is a mission-oriented program, and it assumes that such an improved understanding will better enable the Navy to use the ocean environment to its own advantage.

It must be emphasized that, even though the Code 481 program is mission oriented, research efforts must be, first and foremost, of fundamental scientific importance and results of these efforts must appear in the open and refereed scientific literature.

Code 481 sponsors a sea-going program--funding laboratory experiments, instrument development, and numerical modelling only to the extent that they are integrated with and needed by the go-to-sea research efforts.

Code 481 focuses on the open ocean--generally staying away from near-shore and continental shelf/slope regions for which other federal support is more readily available. Because of limited resources more recently, Code 481 has begun to focus even more on those aspects of the open ocean which appear to be of higher priority to the Navy, for example more support for the upper ocean and less for the equatorial and Southern Hemisphere.

Considering aspects of physical oceanography in which ONR 481 will have an interest in the future, it is worthwhile to consider the following quotes from an article* Columbus Iselin presented at an ONR-sponsored workshop twenty-two years ago:

> "What has been happening recently, and I believe this trend will continue, is that we are becoming much less certain that we can describe the system that we are trying to understand.

*Iselin, C.O'D. 1957. Along what paths is physical oceanography likely to proceed. _In_ Proc. of the Symposium on Deep-Sea Research, W.S. von Arx, ed., Publ. No. 473, Comm. on Undersea Warfare of the NAS/NRC, pp 6-9.

"We see the need for new methods and new equipment, but if the past is any guide, these do not evolve quickly.

"We are beginning to think in terms of synoptic situations, but for the most part our long accumulated data are barely able to describe the average conditions.

"Convenient, long-range, precise navigation remains the number one need in physical oceanography in my opinion. Without it, our ability to describe the near-surface currents over any considerable area will proceed only slowly.

"Assuming that means will soon be found for knowing how the ship is moving relative to the bottom ..., the oceanographer has the more special problem of observing the change of velocity with depth. This is being attacked in a number of different ways and these efforts should be continued at high priority. However, in the end we need a solution that does not require stopping the ship...

"... to describe the motions in the upper 500 to 1000 meters of the water column will require literally millions of observations, and if we are to attack synoptic situations the ships will have to proceed at all practical speeds.

"Thus we come to our next major problem: how to employ the ship most wisely, how to maneuver so as to gain the most effective coverage of an area. The people on the ship cannot know what lies ahead... Let an airplane develop the two dimensional, surface current pattern ahead of the ship so that the people on board can concentrate on the third dimension... Even if the plane had the necessary endurance, the people in it do not. The plane is accumulating information faster then it can be digested and, in addition, a formidable navigational problem is presented.

"Given ideal ships..., better airplanes, adequate navigation, etc., much could no doubt be achieved, but we are not going to get these things quickly, nor can we do much more than urge that they be developed. In the foreseeable future, oceanography will continue to be plagued by the hostility of its environment and the vast areas to be covered.

"We have been struggling for too long with spot observations, separated too widely both in time and in space."

A long-term interest of ONR 481 is directed at better understanding how the atmosphere "forces" the upper ocean. Toward this end, it will be necessary to develop the necessary tools and techniques for observing the three-dimensional near-synoptic density and current velocity fields in the upper ocean.

Iselin has pointed out a number of directions and problem areas which must be faced. However, it appears that significant progress may be made in this direction within the next five to ten years, especially when considering NAVSTAR/GPS (continuous absolute position fixing good to 6 to 10 meters), expendable instrumentation (current shear, temperature, conductivity, sound speed), towed instrumentation (temperature and conductivity chains), hull-mounted instrumentation (acoustic profiling of currents, rapidly-profiling CTD's), moored instrumentation (profiling CTD's with current measurements), aircraft and aircraft instrumentation (the P-3 and improved AXBT's), computers and microprocessors, and satellite products (infrared and microwave for sea surface temperature, radar altimeter for sea surface topography).

SECTION II---AREA SUMMARIES

DESCRIPTIVE PHYSICAL OCEANOGRAPHY

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Four investigators have as their long-range objective the study of the formation of the large-scale water masses and their circulation within the world ocean. They are proceeding toward this common objective with different but complementary methods. These water masses, which are formed and driven by the winds and by heating, cooling, evaporation, and precipitation circulate on various time- and space-scales, among which are the great gyres of middle latitudes, the west-wind drifts of high latitudes, and the deeper flows that carry the denser waters formed in high latitudes into the central oceans and from ocean to ocean and basin to basin.

Bruce Warren is concentrating on the deep western boundary currents as a principal factor in the major basin-wide circulation. His present work is on the flow of the Gulf Stream and the waters near the Grand Banks and on the overall deep circulation of the Indian Ocean. He uses measurements of water characteristics and the density structure in the application and extension of deep-circulation theory. Most recently he has found a deep western boundary current east of the 90°E Ridge in the Indian Ocean and has resolved the problem of the complicated Gulf-Stream/Slope-Water circulation pattern off the Grand Banks.

Valentine Worthington is studying the water masses of the world ocean through volumetric analysis and volume transport of the major currents. He is concerned at present with the seasonal and longer-period variation of the Gulf Stream transport and its relation to the deep mixed-layer 18° water formed in late winter just offshore of the Gulf Stream. He is concerned also with the analagous water masses formed off the Kuroshio, Somali and Antarctic currents which may have similar relations to the major transports of the currents.

Michael McCartney is investigating the modes of formation and renewal of the water masses of the main thermocline and the upper deep layers of the world ocean. He has found certain large-volume "modes", or thick layers of water, each with a narrow range of characteristics. He is examining the possibility that a single process--vertical convection in relatively restricted areas on the poleward sides of the major anticyclonic gyres, and recirculation within these gyres with little alteration, may account for the dominant large-volume central waters of the subtropics. His first published result on this topic is on the subantarctic mode water of the southern hemisphere: he is now applying this concept to the North Atlantic Ocean.

Joseph Reid has been studying the mid-depth and deeper layers of the Pacific, Antarctic, and Atlantic oceans by examining geostrophic shear and distributions on isopycnal surfaces. He finds just southeast of the Gulf Stream and Kuroshio currents a return flow to the west. In the western area, this flow turns southward and then eastward along about 25°N and extends all across the ocean. In the Atlantic the two eastward flows carry water of relatively low salinity compared to the highly saline Mediterranean outflow waters, which extend westward with the return flow south of the Gulf Stream as a warm, saline wedge extending from Gibraltar to Bermuda. In the Pacific the two eastward flows carry high-oxygen waters eastward from the westward boundary, leaving a zone of low oxygen between.

Within the next few years we shall have a useful measure of the volumes of each of the major water masses. With these numbers and the better estimates of the nature and magnitude of the general circulation, we can work usefully on the interactions of these masses within the different oceans and from ocean to ocean. We will hope to have some estimates of the balance of exchange of water, heat, salt, and nutrients within the great ocean system. These will provide the proper background against which theoretical examinations and detailed numerical models can be developed more efficiently and more effectively to improve our understanding of the ocean system. The additional materials on rates of exchange that can be obtained from the isotopes (tritium in particular) within the next few years will be of great advantage in such work, especially in the Arctic, Norwegian-Greenland, Labrador, and Bering seas and in the northern Atlantic and Pacific, and, to a lesser extent, in the Antarctic.

We are limited in this work partly by the small number of investigators. We note that observations of water characteristics and structure are lacking in critical areas and seasons (the Eurasian Basin of the Arctic, the western Weddell Sea, some meridians in the Atlantic, Pacific, and Indian oceans) and that direct current measurements are lacking in critical paths and passages (deep Labrador Sea, Reykjanes Ridge, Indian Ocean, Kamchatka-Komandorskiye Channel).

The present lines of research in descriptive physical oceanography are by no means fully exploited. Work from data in hand has opened up new perspectives (the modes of the water masses, the relation of the Gulf Stream variations to the deep mixed layer, the deep western boundary currents, the complex mid-depth circulation of the northern oceans), and there is reason to expect that more new perspectives will emerge, as the data to be collected by present grants and the results become available.

For more details concerning Descriptive Physical Oceanography see Section V pp 29, 33, 34, 60, 72, 89, 92, 99, 101, 115, 124.

THEORETICAL AND NUMERICAL OCEANOGRAPHY

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Present Status and Recent Progress

Theoretical studies of the ocean utilize applied mathematical techniques such as analytical methods, statistical methods and numerical methods. Since 1960, powerful boundary layer and asymtotic approximations, for example, have permitted analysis of numerous geophysical fluid dynamic problems of rotating, stratified fluids with important implications for understanding ocean circulation. Unfortunately almost all problems are nonlinear or quasilinear and numerical techniques must be used for calculating integrals and solutions for physical understanding. In addition, the assumptions about mean state and geometry are unrealistic.

Statistical techniques such as time series and multivariate analysis applied with physical and dynamic constraints have advanced the interpretation of ocean wave dynamics. The recent work of Magaard (Hawaii) on baroclinic Rossby waves and Briscoe (WHOI) on internal waves are striking examples. The theoretical oceanographer uses the most sophisticated statistical approaches for interpreting the massive quantity of data for understanding.

Numerical oceanography is a young science. The methodology is drawn from numerical weather prediction and numerical analysis. Oceanographers are unable to perform realistic ocean calculations for operational use due to the lack of initial data. In a few instances, the multi-investigator programs such as NORPAX (Haney, N.P.G.S., anomalous circulation), POLYMODE (Robinson, et. al., Harvard, mesoscale eddies) and GATE (O'Brien, F.S.U., and Moore, Nova, Gulf of Guinea Upwelling), INDEX (Hurlburt, Lin, Piacsek, NORDA and Cox, NOAA, Somali Current structure) have collected sufficient data to perform hindcasts of low frequency ocean circulation problems to enhance physical understanding and create detailed hypotheses for future programs. This special branch of numerical oceanography is manpower limited. Both the mathematicians and the physical oceanographers are not producing enough Ph.D.'s capable of solving numerically models containing hyperbolic (wave-type) partial differential equations. At present, approximately ten positions are open in the U.S. Present computers at NRL, NCAR and NOAA are capable of integrating any realistic problem.

Major Accomplishments

In contrast to the 1960's, the theoretical community is closely coupled to the observational community. Dynamicists assist in planning field experiments, participate at sea and interpret available data. Each new experiment is guided by theory and analyzed theoretically. For example, significant advances have been made in understanding the dynamics of the ocean mixed layer: Kraus, Miami; Niiler, Oregon State and Elsberry, NPGS). The MILE experiment was created to achieve a new level of understanding of upper ocean dynamics. Both MILE data and FNWC data for other regions demonstrate severe limitations in the present theory (such as neglect of horizontal gradients). Without the careful analysis by theoreticians of model assumptions, hypotheses for improving our understanding and subsequent use of these theoretical ideas would not be forthcoming.

Future Directions

The ocean is not at a steady state. The atmospheric fluctuations continue to impose large amplitude motions and density perturbations in the ocean. In the 1970's the theoretical community has abandoned the analysis of steady flows and are concentrating on low frequency (greater than tidal periods) flows. Each good field experiment yields data which is grist for the mill and contains surprises for the modellers. Important work on the dynamics of several features are underway: western boundary currents (WHOI, NORDA); Gulf Stream rings (Texas A&M, MIT); mesoscale eddies (Harvard, WHOI, NCAR); upper ocean fronts (Miami, Washington, Delaware); large-scale circulation (F.S.U., Oregon, Miami), effect of bottom topography (Nova, F.S.U., WHOI), Equatorial dynamics (F.S.U., Nova, Scripps, WHOI, MIT). A modelling newsletter (Cambridge) provides a rapid forum for exchange of ideas. The physical oceanographers are planning massive experiments in equatorial regions in the 1980's. Severe limitations apparently exist in advancing our knowledge of upper ocean dynamics (instrument limited), strong ocean fronts (money and idea limited) and nonlinear wave interactions (data limited). Attempts to provide limited-area ocean forecast models for Naval use are being designed at F.S.U. and NORDA.

For more details concerning Theoretical and Numerical Oceanography see Section III pp 2, 4, 11, 14 and Section V pp 7, 25, 30, 36, 39, 47, 69, 73, 79, 80, 82, 91, 92, 94, 96, 101, 103, 104, 126.

LOW FREQUENCY VARIABILITY IN OCEAN CURRENTS

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Present Status and Recent Accomplishments: Community-wide perception of the basic nature and significance of low frequency fluctuations in ocean currents and temperatures has been altered dramatically in the last decade. The principal conclusion from the *Aries* Expedition, widely held in the 1960's, was that the interior of the (North Atlantic, at least) subtropical gyre was characterized by a westward-intensified, highly north-south polarized eddy field dominating a weak mean flow, but results from the past decade indicate a much more interesting and exciting range of low frequency variability. The emergence of the first numerical models explicitly devoted to investigation of eddy dynamics deserves particular note, as does perhaps the discovery of orders of magnitude of geographic variation in the properties of the eddy field. For present purposes, low frequency fluctuations are defined to be time dependent variations in currents and temperatures with periods greater than the inertial period and less than general circulation time scales. The data available point to a broad band process, rich in diversity. Mesoscale eddy time scales have not yet been sharply defined formally, although horizontal scales are almost universally taken as 100-300 km. In the following, the temporal mesoscale is defined to be 10-150 days, with the words eddy or low frequency variability (fluctuations) used for all frequencies higher than general circulation time scales and lower than inertial. Time scales longer than the mesoscale are often called "secular". General circulation time scales are also arbitrary, but normally thought of as greater than a year to several years, and not always distinguished from the secular scale. In the following, secular scales are those longer than mesoscale, and shorter than general circulation time scales, taken to be a few years for practical reasons.

Descriptively, the eddy field has been found to vary sharply in the horizontal in its basic properties such as energy level, Reynolds stresses, relative vertical structure, and spectral shape. This geographical inhomogeneity, involving for example orders of magnitude of variation in energy level, is connected to the pattern of the general ocean circulation. In the North Atlantic, low frequency fluctuations have been found to be most energetic in the vicinity of the Gulf Stream and Recirculation, and in these regions are more energetic than higher frequencies by one to two orders of magnitude. In practice, sampling requirements for estimating the time-averaged properties of the eddy field lead to a data base that may also be adequate for reasonable estimates of the general circulation. As one example, the Recirculation in the North Atlantic has been found to have a strong and narrow, weakly depth-dependent component.

The mesoscale has been studied most extensively in the North Atlantic (by, for example, the MODE and POLYMODE programs), with the secular scale investigated more thoroughly in the North and Equatorial Pacific (by, for example, the NORPAX program). Both scales are observed to exist in both ocean basins. There has been progress in the understanding and prediction of El Niño and of upwelling in the Gulf of Guinea. Gulf Stream or Kuroshio Rings with a diameter of 150-300 km and moving at 3-7 cm s^{-1} would appear as a contribution to the temporal mesoscale. Our information base on Gulf Stream Rings has been sharply enhanced in the last decade. In the North Atlantic the mesoscale is most energetic near the Gulf Stream, and the secular scale picks up moving away from the Gulf Stream into the interior of the gyre. In the MODE-I area the secular scale is the dominant contribution to the eddy kinetic energy in the thermocline (a factor of two higher than the mesoscale).

Two new types of numerical models have been developed in the last decade, in parallel with the acquisition of modern data. Gyre-scale eddy-resolving numerical models yield a spatial coincidence of energetic eddies with the model equivalent Gulf Stream/Recirculation, in qualitative agreement with the available data. In these models, eddies are formed by instabilities in the general circulation, and feed back to drive a deep mean flow (deep downstream increase in transport of the Gulf Stream?). Regional numerical models indicate an eddy field that is less depth-dependent in energetic areas and more trapped to the thermocline in areas of weaker energy and rough topography, also in qualitative agreement with the data available.

<u>Prospects for the Future</u>: One might envision a vigorous program of World Ocean Exploration in the next decade. The data base for the low frequency field is rather sparse throughout the oceans. The weakly depth-dependent segment of the general circulation is virtually unexplored. One would also anticipate the addition of realistic topography to gyre-scale eddy-resolving numerical models.

We are in the process of discovery of the fundamental characteristics of the eddy field and the weakly depth-dependent component of the general circulation. It is an exciting time, and the next decade should be very rewarding in this area of research, if sufficient resources are made available. The entire spectrum of existing technology would probably be useful in this exploration, and new techniques such as acoustic tomography should be exploited as development and testing are completed. The main strategy of geographical exploration is to intercompare data from geographically distinct areas. An interesting next step would be to intercompare observations from different ocean basins, the North Pacific vs. the North Atlantic for example.

For more details concerning Low Frequency Variability see Section III pp 2, 11, 12 and Section V pp 6, 31, 32, 33, 34, 40, 41, 54, 76, 82, 91, 93, 98, 99, 103, 108, 110, 111, 112, 118, 119, 126.

LARGE-SCALE, WIND-DRIVEN, GENERAL CIRCULATION IN THE INTERIOR OCEAN

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The classical theory of the wind driven general circulation in the interior* ocean, forming the basis of nearly all present-day ocean modeling efforts, was proposed by Sverdrup over 30 years ago. In this theory, the zonal currents in the ocean interior are related to the rotational component of the wind. Sverdrup himself was able to apply this theory in explaining the then puzzling existence of the North Equatorial Countercurrent in the Pacific in terms of the rotational component of the Trade Winds. A few years later Munk expanded this application by showing that the theory could reproduce the qualitative features of the Subtropical and Subarctic gyres of the North Pacific in terms of the rotational components of the Trade Wind and Westerly wind systems. Partly because of the initial apparent success of this theory in explaining the qualitative aspects of the general circulation, subsequent years saw little experimental effort designed to test quantitatively the assumptions and conclusions of this theory. However, in 1976 this situation changed with the inception of the Anomaly Dynamics Study (ADS) in the mid-latitude North Pacific.

The ADS program is a multi-university cooperative program within NORPAX, containing both experimental and theoretical components studying the transient behavior of the North Pacific Current.

The ADS field experiment consists of measuring the surface wind-driven flow and the thermocline structure of the North Pacific Current, from 30° - 50°N, 180° - 130°W, on a monthly basis since January 1976. By investigating how the surface currents and structure of the main thermocline of the North Pacific Current responded to the very severe autumn/winter storm forcing by the Westerly Wind System in 1976-77, key assumptions vital to the classical theory of the wind-driven general circulations are able to be tested (at least tentatively): (1) the assumption that the horizontal mixing of heat, salt and momentum by baroclinic meso-scale eddies in the ocean interior is negligible has

* Away from the direct influence of the western, eastern and equatorial boundaries.

been shown to be true in this part of the ocean; (2) the assumption that thermohaline processes in the upper 500 m of the ocean interior are negligible has been shown to be false here; (3) the assumption that the wind-driven surface currents in the ocean interior move 45° to the right of the wind, in the manner proposed by Ekman in 1905, has been shown to be false, moving more like 30° ±5° to the right of the wind; and (4) the assumption that the main thermocline is displaced vertically by the convergence and divergence of surface wind-driven currents has been shown to be true.

The surprising result from the ADS field experiment is that although many of the assumptions important to the classical theory have been found to be true (if somewhat modified), the influence of thermohaline processes (neglected in the classical theory) have emerged as dominant in modifying the strength and location of the North Pacific Current. The response of the ocean thermocline structure to the rotational component of the wind was found, but its influence upon the character of the North Pacific Current was small compared to that of thermohaline processes.

In the future, it will be important to establish those areas of the interior ocean where the general circulation does not conform to the classical theory put forth by Sverdrup. As indicated from the ADS field experiment, the interior mid-latitude North Pacific is one such area, wherein thermohaline processes dominate those proposed in the classical theory. To gain further understanding in this area, large-scale experiments, of which the ADS is a prototype, will be needed to establish the vertically integrated budgets of heat, salt and momentum, as well to determine how these quantities are transported horizontally over large distances. In addition, small scale experiments, of which the recent MILE (Mixed Layer Experiment) is a prototype, will be needed to establish the processes important for vertical transfer of heat, salt and momentum over the upper few hundred meters of the ocean. To accomplish this in the often severe weather conditions of the mid-latitude oceans will require the use of remote sensing by satellite (e.g., surface topography, wind/wave field), expendable devices (e.g., measuring temperature, salinity, and velocity with depth), and special ancillary experiments designed to calibrate important physical processes in terms of more readily measureable parameters. This kind of large-scale experimental effort will require dedicated funding over a period of years and informal coordination between many subspecialties in the oceanographic community.

For more details concerning Large-Scale Wind-Driven Circulation see Section III pp 4, 11 and Section V pp 5, 13, 15, 22, 23, 29, 31, 47, 49, 57, 66, 67, 69, 74, 76, 110, 119.

THE NEAR SURFACE OCEAN

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The past two years have seen an accelerating pace of investigation of the oceans' upper layers. Phenomena of interest range from the turbulence responsible for creating the mixed layer, through the energy dominant surface waves and the internal waves and inertial motions connecting mixed layer and deep ocean, and on to processes having large horizontal scales such as the surface manifestations of mesoscale eddies or the seasonal thermal cycle. Most of these phenomena are discussed elsewhere in this report and what follows focuses on those aspects central to the near surface ocean.

Of upper ocean phenomena, the best understood are generation and propagation of surface waves. Much remains to be discovered about the mechanism of momentum transfer from wind to waves and currents, but prediction of energetic surface waves is primarily limited by ignorance of the detailed wind field. The distribution of energy by wavelength and propagation in a typical sea-state is reasonably well understood, enough so that remote sensing of surface waves is a viable technique for observing winds and surface currents.

Recent intensive field programs such as GATE (Global Atlantic Tropical Experiment) and MILE (Mixed Layer Experiment) have documented the presence and temporal variability of an energetic "sea state" of internal waves and inertial motions in the mixed layer and seasonal thermocline. Combining results of various observational methods such as Paulson's thermistor chain tows, Pinkel's long range sonar velocimeter, and more conventional moored instrumentation (see reports by Burt, Davis, de Szoeke and Halpern) should provide a growing empirical description of the internal sea state. As the volume of data grows the empirical description may approach in adequacy that which is known of the deep ocean internal wave energy and suggestions about the mechanisms of generation and decay will result from the variations observed in time and geographical location. Following the course found so successful in understanding surface waves, laboratory studies of internal waves and similar scale motions generating mixing and upper ocean turbulence bridge the gap between idealized theory and highly complex oceanic truth (see reports by Browand and Maxworthy).

Motivated by a desire to predict large scale (tens to thousands of kilometers) features of the upper ocean, theoretical and observational investigations of the mixed layer have accelerated over the last few years. Theoretical models of the mixed layer (the one discussed in this report by Elsberg and Garwood is an example) focus on atmospheric inputs of heat and momentum causing storage of heat in the mixed layer and redistribution by vertical mixing processes related to wind forced currents. Work continues on the transfer processes between atmosphere and ocean (see reports by Ling and Kao and by Burling and Pond) with a focus primarily on increased accuracy of describing reasonably well understood processes. Observational programs in the oceanic mixed layer, on the other hand, focus on describing a complex state of variability very much different from the vertical mixing concept of theories. Experiments designed to look at the mixed layer in detail (like MILE, JASIN, GATE and POLE discussed in this report) show marked lateral variability of temperature and salinity, indicating lateral mixing and formation of small fronts. Velocity fields vary rapidly in the horizontal suggesting the vigor of eddy processes. Understanding of these lateral variations is clearly a critical need in upper ocean research. In part new theoretical frameworks are required but, in large measure, progress is held back by our inability to observe continuously in time a volume of the upper ocean.

Because of the growing interest in the three dimensional mixing processes in the mixed layer and seasonal thermocline, it is encouraging that new observational tools promise to allow more intensive sampling of the upper ocean. Not only are methods of observing turbulence and microstructure being perfected (see Lange's summary in this report) but survey tools, permitting sampling of volumes of upper ocean are being developed. Improved methods of rapidly gathering profiles of temperature and salinity over a horizontal pattern (see, for example, reports by Sippican and Paulson), obtaining reliable time series of upper ocean currents (cf. Davis, Halpern, Pinkel, Wunsch) and even spatial sampling of velocity (cf. Sanford, Stommel and Regier) hold great promise. It is expected that concerted observational programs employing such improved instrumentation will provide new insights into mixed layer response to atmospheric forcing and deep ocean eddy motions, and optimistically, into the formation and behavior of oceanic surface fronts.

For more details concerning The Near Surface Ocean see Section III pp 4, 6, 9, 11 and Section V pp 8, 10, 15, 16, 23, 25, 30, 44, 45, 53, 56, 66, 70, 85, 86, 87, 98, 106, 108, 110, 118, 119, 126.

INTERNAL WAVES: OVERVIEW

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The past ten years have seen an intense effort in the study of internal waves and major progress has been made, especially in the deep ocean away from the direct influence of strong currents, atmospheric effects, and boundaries. We are now able to state, with good statistical confidence, what the space-time spectrum of the deep,open-ocean internal wave field looks like, and a structurally-sound theoretical basis for why it looks that way has been proposed. The kinematical description of the deep internal waves is therefore substantially complete. Although continued modest geographical exploration is still useful, the major effort of the next few years will be toward the energetics of the problem: where does the internal wave energy come from, what does it do, and where does it go? Although still speculative, one intriguing possibility is that the main function of the internal wave field is to provide a means whereby large-scale, slow, mostly-horizontal ocean motions may be converted to small-scale, rapid, mostly three-dimensional motions that tend ultimately toward the dissipation scales of a few cm and smaller.

The picture of the upper-ocean internal wave field is considerably less well-developed. In contrast to the deep-ocean case, the upper-ocean field seems to be time-variable, geospecific, and sometimes directional, although these conclusions are ambiguous due to the disparate way in which the upper-ocean measurements have been made and the data analyzed. The technological challenge of making internal wave measurements in the upper ocean is not helped by the additional difficulties imposed by the scientific structure of the problem, namely rapidly-changing buoyancy frequency (Brunt-Väisälä) profiles, propinquity to a boundary (i.e., the surface), and strong and variable forcing by the atmosphere.

The principal accomplishments of the past two years have included the final documentation of several major field experiments, the proof-of-concept of several new acoustic remote-sensing techniques and upper-ocean instruments and the performance of one major upper-ocean experiment (MILE) and the preparations for another (JASIN), both of which have significant internal wave components.

The efforts of the next few years will include the workup of MILE, the performance of JASIN, increased study of the overlap between internal waves and finestructure, particularly in the 1-10 m vertical scale region, several uses of the new acoustic devices, and continued theoretical investigations of non-linear interactions and internal solitary waves.

Two important kinds of field efforts are only in the talking stages, but are crucial to the development of our understanding of especially upper-ocean internal waves: heavy-weather experiments, and long-duration experiments. For these to be successful, we will need continued validation of our instrument performance near-surface, particularly with respect to bio-fouling and wave-zone behavior, and will necessarily have to integrate the studies with larger-scale ocean studies and meteorology/air-sea interaction studies.

For more details concerning Internal Waves see Section III pp 6, 9, and Section V pp 8, 20, 24, 59, 87, 98, 116, 126.

FINE AND MICROSTRUCTURE

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Ultimately all heat, mass and momentum are distributed and constantly redistributed within the ocean by small-scale processes. The understanding of small-scale variability is relevant to Naval needs in ASW, evaluating sonar performance, subsurface communication technology, contaminant dispersal, and other related areas of concern.

The study of microprocesses (of scales less than a few tens of meters) has two goals: to understand the physics of stratified fluid transports of heat, mass and momentum, and to characterize the variability of small-scale features in relation to the many and differing generative mechanisms.

Most measurements have been made by vertical profiling, since heat and salt vary most rapidly with depth, rather than laterally. However work in the last year, ranging from benthic measurements of mixing and advection, to near-surface, storm-induced variability, suggests that lateral advection of the remnants of a previously three-dimensionally stirred body of fluid may be the dominant source of transport of heat and salt, both in the horizontal and vertical directions. This is astounding in view of the sharp gradients (and increased vertical diffusion that must result) that are always seen in vertical profiles of the oceans' heat and salt fields.

Our inability to construct even a simple heat budget for a patch of the ocean based from fine and microstructure measurements remains the single most pressing problem in this field, and argues strongly for a redirection of effort to a survey capability. We believe we understand generative and dissipative phenomenologies in the ocean, but we cannot yet understand their interrelationships.

Recent Progress

Significant progress includes the first repeated yo-yo profiling of an active mixing regime, and the resultant highly stable statistics (in the MILE experiment). We may now be able to examine in detail flux rates of heat, and higher-order statistics of one mechanism of small scale variability--that of shear-induced turbulence. Another significant step has been the discovery that lateral variability of small-scale processes is so large that nearly-simultaneously dropped instruments fail to intercompare at scales of interest in the diffusive/advective process (in the FAME experiment).

The recent, careful work on benthic boundary layer mixing and burst turbulence suggests that energy from low frequency internal waves results in locally-generated small-scale variability that may advect into the deep ocean, and may in fact be a dominant source of fine structure in the deep ocean.

Work has begun to unravel the differences between transient fine structure created by the straining motions of internal waves, from that of persistent, repeatably observable structures. The behavior of internal wave spectra derived from temperature measurements has been studied, and the correction for finestructure contamination is now reasonably well understood as is our ability to separate out true fine structure features from that due to internal waves.

The vertical profiling of shear (two of the nine components of the rate-of-strain tensor has revealed that the internal wave field appears symmetric in up-welling and downwelling wave energy, except near the surface, and at inertial frequency waves, where a prominant downward flux of energy has been observed. Finally, work has just begun to 1) seriously intercompare sensor technology used on profiling and towed instrumentation, and 2) coordinate the many shear and small scale temperature measurements into an atlas of observations geographically.

Questions raised by recent work

How is vertical heat flux influenced by the lateral advection of intrusive features? What is the lateral variability of small-scale processes, and what is a heat budget for a region of the ocean? Why was it that a 40-know wind driven sea of 20-feet appeared to not alter the variability of processes just 5 meters below the surface, during and after the storm? Just how effective is bottom topography at advecting small scale features to the mid-ocean? And importantly, how do we best expand our measurement capability to survey small scale variability synoptically?

For more details concerning Fine and Microstructure see Section III pp 6 and Section V pp 2, 10, 19, 20, 24, 38, 43, 63, 64, 70, 83, 98, 121.

REMOTE SENSING OF THE OCEANS

The Program of the Office of Naval Research

by

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For centuries oceanography has depended on sparce measurements made to great depth from a few ships plodding their way through the seas. Now we are turning from these intense but local studies toward a global view of the oceans, and are seeking means to survey the motions of entire ocean basins and the processes governing these motions. One approach to the problem monitors those variables that are sensitive indicators of the state of the ocean as a whole or that represent the integrated effect of processes over the oceans. But these studies must be supplemented by detailed observations of large areas. This is the domain of remote sensing, a neologism for tools as varied as the processes and variables they seek to observe.

Not surprisingly, the most widely used techniques are the oldest. Infrared and visible images of the sea made by operational weather satellites are now specially processed to enhance oceanic features, and are routinely used to map features having thermal contrast such as the edge of the Gulf Stream. Among contractors to the Office of Naval Research, Düing and Brown have studied long waves in equatorial regions and the dynamics of the western Indian Ocean, particularly the Somali Current; while Bernstein, observing areas off the California coast, has shown that even weak thermal features are often representative of deeper structure and can be used to study currents. A number of investigators, including Richardson, Mollo-Christianson, and Bane and Brooks, are studying the Gulf Stream using satellite images; Holyer uses LANDSAT images to observe the Pacific; and Roden uses satellite data and surface analyses to study the motion of oceanic fronts.

In contrast to these varied uses of images from the meteorological satellites, the Navy's basic research in support of experimental satellites is considerably weaker, partly because the academic community prefers to wait until a new technique is proven before using it in their work, partly because skills required to develop satellite techniques are usually not found in oceanographic laboratories. This latter has led to cooperative work between oceanographers and space scientists. I work with Vesekcy at Stanford's Center for Radar Astronomy to determine the ability of synthetic-aperture radars to observe ocean waves, and with NASA laboratories to determine if radiometers on SEASAT-A will be able to measure oceanic rainfall accurately. At Lamont, Talwani uses GEOS-III altimeter and orbit data from NASA Wallops Flight Center to study the oceanic geoid, and Gordon expects to determine if these data contain oceanographic information distinct from the geodetic information.

As oceanographers turn toward satellite instruments, they begin to face the problem of handling large amounts of data. Satellite images containing thousands of points must be corrected for the distortion of viewing the Earth from space, enhanced to bring out oceanic features, and stored. Initially this can be done at large laboratories operated by NOAA and NASA, but sooner or later it becomes necessary to do this closer to home with more control over the manipulations of the data. Düing and Brown now operate a system to handle meteorological satellite data; and Bernstein proposes, with help from NASA, NSF, and the Jet Propulsion Laboratory, to build a system to receive and process data from the Pacific obtained from NIMBUS-G, TIROS-N, and SEASAT-A.

Remote sensing is not always done from space. HF radars, operating at decameter wavelengths from coastal sites, observe the sea out to ranges of 200 km or more. Lipa, working with Howard, has developed a method of using a single radio wavelength to measure the directional spectrum of ocean waves. Working with Howard and Teague, I have observed the rate of growth of 7-second ocean waves as a function of angle to the wind and the rate at which they are flattened by an opposing wind.

The future for remote sensing is promising. SEASAT-A and instruments on two other satellites will begin observing the oceans soon after their launch this year. But if data from these satellites are to be useful, and if the limitations of the satellite instruments are to be understood, the Navy must continue to fund both research into processes influencing the interpretation of data from satellite instruments, and research that uses satellite data to study the global oceans. Eventually, we hope that our perspectives will broaden to the point where we can begin to understand entire ocean basins.

For more details concerning Remote Sensing see Section V pp 3, 6, 12, 40, 55, 56, 65, 77, 86, 106.

OCEANIC FRONTS

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In its broadest sense, and as it was apparantly applied in accepting contributions to the AGU/ONR sponsored Chapman Conference on Oceanic Fronts last fall, a front is simply a surface of discontinuity between two water masses. As a result the conference included a wide range of topics which, at first glance, may seem to have little in common beyond the definition. One of the first tasks facing us in the future is clarifying what oceanic fronts do have in common.

Using the conference as a barometer of present interests in fronts, the first major subdivision can be made between coastal and open ocean fronts.

Coastal fronts exist by virtue of there being a coastline present and are strongly influenced by both the local bottom topography and the wind stress components relative to that coastline. The two most discussed examples of coastal fronts were those related to the shelf-slope break and to coastal upwelling. Environmental concern has provided a new impetus to studies of coastal dynamics along the eastern coast of the U.S. which includes, as one important facet, the study of the frontal zone boundary of the shelf waters at the shelf-slope break. The CUEA project (supported by the IDOE office of the NSF), meanwhile, has sponsored several case studies of upwelling off the western coasts of the Americas and Africa. Characteristic of the phenomenon are frontal zones at the boundary of the upwelling regions.

Open ocean fronts are divisible in terms of their steadiness or permanence. Large currents, such as the Gulf Stream, often satisfy the definition of a front, though frontogenesis and frontolysis are not clearly associated with them. (Immediate exceptions arise when the current is seasonal, such as the Somali current). To the above can be added the frontal zones that mark the edges of a major water mass, such as the Polar Front, or result due to the topographic disturbance of a sill, or a mid-ocean ridge, to the movement of a water mass.

In contrast to the above are those mid-ocean fronts which are intermittent and therefore the study of frontogenesis and frontolysis is the whole key to their presence. These occur in broadly defined surface convergence regions, such as in the sub-tropics of the Atlaatic and Pacific Oceans, but on smaller scales may be more ubiquitous. Recent studies of mid-ocean fronts have approached frontogenesis from two directions: above and below. Above is the atmospheric wind field and its local forcing; below is the mesoscale eddy field. Both can and probably do cause the local intensification of lateral gradients which result in well-defined, albeit intermittent, frontal zones. The prospects of significantly increasing our understanding of frontogenesis is linked to the increased operational use of remote sampling techniques such as satellite sea surface temperature, surface wind measurements, and drogues and the air launched XBT (and XSTD?).

The collapse of frontal zones, on the other hand, is most likely to be understood from smaller scale observations made from a ship and then introduced to theoretical models. The new methods of measurements which result in fine scale observations of density and current have yet to be applied systematically to the study of frontolysis. Here, the study of the variety of fronts have a common interest though emphasis may vary. Mixing is occurring in all frontal zones and the interleaving of water masses as a prelude to mixing has been observed in many. The richness of fronts permits the study of the mixing process in a wide range of stability parameters, frictional factors and forcing mechanisms.

For more details concerning Oceanic Fronts see Section V pp 6, 7, 36, 58, 59, 78, 95.

WESTERN BOUNDARY CURRENTS

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US oceanographers are participating in several year programs in two western boundary currents (WBC's), the Gulf Stream (GS) and the Somali Current (SC) and occasionally in programs in the Kuroshio region. Present experimental work in the GS region is focused on GS-rings, topographic Rossby waves and meanders, the flow into the Caribbean and the deep Western Boundary Undercurrent. Research in the SC region concentrates on the response of the ocean to the monsoon onset, the interaction of the boundary current with very large eddies and coastal upwelling. Observations since 1975 are showing strong interannual variation and are resulting in preliminary eddy statistics. Supporting the field work are theoretical investigations on the formation and decay of eddies and rings, their significance to the large-scale circulation and their potential role in oceanic heat budgets. GS fluctuations in the period range from 4 to 25 days are interpreted in terms of topographically or atmospherically forced waves or as baroclinic instabilities. Several model studies (mostly numerical, one dishpan) are underway to investigate conditions in a strong cross-equatorial boundary current.

Recent results span the spectrum from large-scale to meso-scale processes. The interior transport of the subtropical gyre is found to be consonant with the linear dynamics of the Sverdrup curl-of-the-windstress relation. Computed interior transports compare well with directly observed transports in the Florida Straits. It is very likely that the directly wind-driven segment of the North Atlantic gyre is reflected in the 30×10^6 m^3/sec moving through the Florida Straits, with a downstream transport increase induced by the eddy field, especially at depths below the main thermocline. The separation mechanism of the GS and other WBC's from the coast is determined by the intensity of thermal driving as well as by wind stress. New information on GS rings and on SC eddies indicate that southward propagating cyclonic rings are typical for the GS, while northward moving anticyclonic eddies are typical for the SC. By far the most energetic fluctuations in the GS fall in the period range from 4 to 25 days contributing about 60% to the overall variance (tidal motions contribute about 25%, seasonal fluctuations about 12%). While there is high correlation between oceanic and atmospheric fluctuations, particularly around periods of 5 and 11 days, the generation mechanism of these fluctuations and their precise nature are still obscure.

The great significance of the oceanic component in global heat budgets has recently been demonstrated; it has been emphasized that WBC's are carrying most of the meridional heat flux. An excellent demonstration of these general results is based on the impressive contributions by the USSR in the framework of the Cooperative Study of the Kuroshio since 1965; their analysis reveals evidence that long-period fluctuations on a time scale of 5 years are constituting an important climatological link between the Kuroshio and the California Current (similar observations do not exist for other WBC's).

Most problems encountered in the current research relate to inadequate observation techniques, but there are also conceptual difficulties. Our observation techniques are ill-matched to decipher the governing physics in WBC's. We are often defeated by temporal and spatial inhomogeneities, i.e., we need integrative measurements rather than point measurements. The dominant heat and momentum exchange occurs in the upper layer of the ocean but surface platforms are difficult to maintain over long time periods, let alone in the intensive flow of WBC's. Technical and conceptual problems are often closely related. Heat flux computations require a reliable reference temperature; how can it be determined? Another problem concerns the question, on which spatial scale the concept of negative viscosity should be applied? Strong kinetic energy flux can be directed from fluctuations to mean flow and vice versa on a local scale. On large scales these fluxes appear to be smaller. On which scale are energy flux (and heat flux) considerations relevant to a particular problem?

It appears to me that work during the next few years should concentrate on two WBC regions: in the Atlantic from 15^{o}N to 40^{o}N and in the Indian Ocean from 5^{o}S to 25^{o}N. These regions include a slowly-varying mid-latitude current and a quickly-varying low-latitude current. Both systems play an important role in meridional heat transport contrasting a positive, northward heatflux in the GS and negative, northward heatflux in the SC. It appears mandatory to make a commitment to two long-term key programs:

1. Establish temporal and spatial statistics of eddies in both regions as well as eddy decay and formation time, keeping in mind that not the eddies themselves, but their effect on the circulation, are of interest. This work should preferably use remote sensing methods and large numbers of satellite-tracked drift buoys and sonar-tracked subsurface drift buoys.

2. Begin monitoring programs in selected areas, for example:

   a) Start with an intensive two-year pilot program in the Florida Straits to determine the most effective way for monitoring mass transport and temperature; a less intensive monitoring program should follow for the remainder of the next decade. For reference purposes, repeated temperature sections should be run at the same latitude across the entire Atlantic, say four times a year, and if possible, also along a shorter cross section off Cape Hatteras to monitor the deep thermal structure.

   b) Begin monitoring "simple" variables such as the recently observed strong temperature changes at coastal stations between 4^{o}S and 10^{o}N off East Africa, relating to monsoon onset, the passage of large eddies and coastal upwelling.

Programs of a shorter life-span supporting these two long-term key programs will automatically result. Development of instruments and methods will indirectly accompany the long-term programs. Theoretical work supporting these observational efforts should include frontal models in isentropic coordinates. Air/sea interactive meso-scale models, incorporating WBC's are urgently needed for meaningful experimental design in the next decade.

For more details concerning Western Boundary Currents see Section III pp 2, 4 and Section V pp 3, 9, 12, 13, 27, 34, 40, 58, 67, 77, 92, 93, 94, 102, 103, 109, 111, 112, 121.

BENTHIC BOUNDARY LAYER

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Experimental studies of the abyssal-benthic boundary layer began a dozen years ago. The earliest studies confirmed the existence of a shear-turbulent boundary layer extending 5 to 50 meters above the deep-sea floor. Profiles of mean velocity and temperature in the lower 10-20% of the boundary layer were found to be similar to those in steady non-rotating turbulent flows in the laboratory, while the upper part of the layer was complicated by effects of time variation and rotation. Recently, Weatherly has developed numerical models for the entire boundary layer, and testing of these with observational data is in progress.

A bottom mixed layer is often observed to extend to elevations far above the turbulent boundary layer thickness. Armi has investigated the bottom mixed layer and he suggests two alternative explanations: boundary layer mixing by upstream topographic features, or roll-wave mixing at the top of an insufficiently thick layer, caused by an internal Froude number instability.

Interest in the turbulent structure of the benthic boundary layer was aroused when Gordon, at the Naval Research Laboratory, measured the large scale (> 1 meter) turbulence in a tidal river, and reported that most of the turbulent transfer of momentum occurred in occasional events of high Reynolds stress. These events were presumed to be manifestations of quasi-ordered structural developments, called 'bursting' in the laboratory flows where they were initially discovered. Recently, apparatus for measuring turbulence in the deep sea has been developed. Williams' acoustic system can resolve scales of 10 cm, while Giselher Gust's metal-clad hot wires can resolve a fraction of a centimeter. Experiments with Williams' system in the abyssal boundary layer will begin in 1978.

Interaction of the benthic boundary layer with the sea bed occurs because of the various flow drag characteristics of different bedforms and sediment suspensions, and because of the potential ability of the current shear to transport bottom sediment. J. Dungan Smith (under NSF and Dept. of Energy support) has studied these interactions on the continental shelf and has developed numerical models for the processes involved. In the deep Florida Straits, Wimbush has related time-lapse motion picture observations of sediment motions to recorded current speeds in the boundary layer.

Benthic animals form mounds and depressions which influence the overall boundary layer flow through their effective roughness. Also the animals can increase or decrease the erodibility of the bottom sediment. These effects have been studied by Donald C. Rhoads (under NSF support) and others.

A characteristic feature of the benthic region is the intensity of the physical-geological-biological-chemical interactions that are occurring there. Because of the interdependence of processes in these different disciplines, progress in any one field of benthic research has often been hampered in the past by a lack of knowledge of influential parameters from other fields of endeavor. Joint interdisciplinary experiments are obviously needed in the future.

At present, the time is ripe for solving two physical problems of the benthic boundary layer. The first of these is the problem of predicting the turbulent flow properties near the bottom from known flow conditions above the layer. The second problem is that of predicting the response of the sediment to the near-bottom turbulence. In fact these are not really separate problems, because the sediment moving in response to a competent flow may create bedforms or dense near-bottom suspensions which then have a marked effect on the overlying turbulence. The joint solution of these problems would enable us to predict sediment dynamics from the hydrodynamics of the flow outside the boundary layer. But different sediments in different regions will require separate study, until we learn how to parameterize properly the sediment erosion properties.

In a typical deep-sea site, the sediment is rarely disturbed. Apart from the occasional stirring by a benthic animal, the sediment is unmoved until an event of unusually strong bottom flow, and associated turbulent shear stress, occurs. It is quite unknown how long an experiment is required for the results to be considered representative, but a duration of a few days, or even weeks, is probably too short at most deep sites.

Initially, at least, it seems wise to concentrate on high-energy locations where the turbulence is more vigorous, and competent currents are more frequent. Preliminary planning for a high-energy benthic boundary layer experiment (HEBBLE), involving principally physicists and geologists, was conducted at a workshop in Colorado in March 1978. An often discussed candidate region was the continental rise off Nova Scotia and New England, where the Western Boundary Undercurrent sweeps rapidly across the bottom. Current meters and turbulence sensors would be used to study the flow, and cameras and recording transmissometers (or nephelometers), together with sediment traps, would be used to monitor bed-load and suspended-load sediment transports. Box cores of sediment from the region would be brought to the lab for grain size and other analyses. Hydrographic density structure would be monitored with a ship-lowered CTD, or perhaps a benthic cyclesonde array. If the mixed layer thickness were recorded upstream and downstream of the New England Seamounts, the mixing effects of these topographic features could be investigated.

Such an experiment, conducted jointly by physicists and geologists, would greatly improve our understanding of the dynamic processes occurring in the benthic boundary layer, and would lead the way to still broader experiments in the future.

For more details concerning the Benthic Boundary Layer see Section V pp 2, 92, 100, 117, 122, 123.

SECTION III---LARGE PROJECT SUMMARIES

GULF STREAM RING EXPERIMENT

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A ring is formed when a Gulf Stream meander pinches off from the main current and forms an intense eddy of swiftly flowing water. During the formation of a cyclonic ring a sizeable mass of slope water originally located north of the Stream and containing its own biological and chemical components is carried south of the Stream and into the Sargasso Sea. Rings are large eddies up to 200 miles in diameter; they occur frequently in the northwestern Atlantic and are of primary importance to the physics, chemistry, and biology of the region. Recent numerical modeling studies suggest that rings vitally affect the size and shape of the entire Gulf Stream gyre including both the near surface and deep water. Rings also affect the nearby water in which they are imbedded. Although we know a considerable amount about the general nature and importance of rings we have lacked sufficient information to predict or model their behavior. Thus a group of investigators has come together and is conducting a multidisciplinary study of cyclonic Gulf Stream rings. Both the Office of Naval Research and the National Science Foundation are funding this work. The long-range objectives of the experiment are: 1) to learn about ring dynamics, mechanisms of ring decay, and the interaction of rings with the surrounding ocean, 2) to acquire data in order to develop and test physical, chemical, and biological models, and 3) to measure and describe the horizontal and vertical structure of biological populations, chemical constituents, and physical properties and to relate these to the changes in gross ring structure.

In order to implement these objectives we carried out an interdisciplinary field program during 1976 and 1977. The program focused on the time evolution of two Gulf Stream rings and consisted of the following: an initial search by NAVOCEANO AXBT surveys to find a newly formed ring; a series of cruises with which we used XBT surveys to measure the size and shape of the rings; CTD-O_2 profiles along with discrete samples for chemical analysis to measure the deep ring structure and water properties, freely falling instruments to measure velocity structure, and net tows and trawls to measure the biological structure; and the use of free-drifting satellite-tracked buoys and satellite infrared imagery to follow the movement of the rings. The time series data consists of the results of four major interdisciplinary cruises which were spaced at intervals of three months and a series of shorter cruises which were obtained on a ship-of-opportunity basis and which helped fill in information in the intervening times.

Our major effort during 1976 and 1977 was preparing for the field program and carrying it out. Because of the intense activity during that period associated with the cruises we have only recently been able to begin a careful analysis of the data that we obtained. We expect to finish most of the analysis in 1978 and 1979.

Our major accomplishment to date has been to define many aspects of ring behavior in the Sargasso Sea. During the experiment we followed from birth to death two cyclonic Gulf Stream rings each of which had a lifespan of seven months. In addition we surveyed three other cold core rings and obtained comparative data in the Gulf Stream, in the Slope Water north of the Stream and in the Sargasso Sea south of the Stream. A complicated picture of rings is emerging from the data. Evidence suggests that one ring split into two pieces and that two other separate rings collided. Several rings coalesced with the Gulf Stream. Some of these turned into open meanders, others were advected downstream and others reformed as modified rings.

For more details concerning the Gulf Stream Ring Experiment see Section V pp 91, 93, 98, 103, 112, 121.

Project Title: "INDEX: An Oceanographic Contribution to International Programs (FGGE/MONEX and IOC/CINCWIO) in the Monsoon Region of the Indian Ocean"

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Scientific Objectives

The purpose of the INDEX experiment is to explore the ocean's complex interactive role with the Indian summer monsoon. 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.

Objectives of the Project

INDEX has three specific objectives. They are:

1) To study the onset of the Somali Current, particularly the evolution and vertical structure of the different inflows and outflows.

2) To study the vertical distribution of current through the whole water column along the equator, with particular emphasis on its zonal and temporal variation in the upper thousand meters.

3. To study the variation in time and space of the eddies off East Africa, and the relationship between the regions of upwelling, the eddies, and the main boundary current.

Current Status

Preliminary field work has been carried out since 1973, with especially intense observations in 1975 and 1976. The data have been and are being studied and compared with theory, in order to design a significant experiment for the FGGE (1979) period. The 1979 experimental design was begun at the FINE workshop in the summer of 1977 and refined at an INDEX meeting in January, 1978, and will be finalized at a SCOR WG47 Indian Ocean Panel meeting in Paris in the fall of 1978.

Major Accomplishments

A number of important results have come from the pilot studies for INDEX. In May-June, 1976, James Luyten and John Swallow made acoustic profiling sections to the bottom along 53°E. The prime result from the measurements was that the vertical structure of the horizontal velocity in the vicinity of the equator is characterized by small vertical scales, of order 50-100 m. throughout the water column. This structure is equatorially trapped and has a time scale of at least one month.

The other major finding to date, based on the observations of Walter Duing, John Bruce, and Lloyd Regier, is that the time-dependent structure of the Somali Current is more complicated than some simple models would suggest. In particular, large-scale eddies, generated near the equator and drifting slowly up the coast, are intimately related to the major current, so that they probably should be viewed as part of the same system. Further understanding of these major preliminary results is the principal aim of the 1979 INDEX experiment.

Additional Information

INDEX is a multi-institutional, multi-national undertaking and is part of a broader FGGE oceanographic program being coordinated by SCOR WG47. Other countries besides the U.S. involved in INDEX or expecting to work at sea in the Indian Ocean in 1979 include the United Kingdom, West Germany, the U.S.S.R., France, and Australia. Much of the local work has been accomplished through significant cooperative efforts with both Kenya and Somalia. Support comes from NSF/GARP, NSF/IDOE, and NOAA, as well as ONR. Measurements are made from ships of opportunity as well as research vessels (e.g., Exxon tanker, U.S. Navy vessels). The Naval Oceanographic Office has helped coordinate work from U.S. Naval vessels.

For more details concerning INDEX see Section V pp 12, 13, 27, 57, 62, 67, 73, 79, 82, 102, 126.

JOINT AIR-SEA INTERACTION PROJECT (JASIN)

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Background

JASIN is a United Kingdom-initiated program and a U.K. contribution to the Global Atmospheric Research Project (GARP). Proposed by the Royal Meteorological Society in 1966, there have been field trials in 1970, 1972, and 1977, all devoted to preliminary exploration of scientific and engineering aspects of the intended major joint experiment, which will occur in July-September 1978 northwest of Scotland in an area bounded approximately by 57-60°N, and 9-14°W.

The U.K. Royal Society is the lead agency, Professor Charnock is the Scientific Director, and Dr. Raymond Pollard is the Scientific Coordinator. Because of the number of different laboratories and groups participating from the U.S., I am acting as U.S. Coordinator for the project.

JASIN Objectives (quoted from a JASIN planning document)

(1) To observe and distinguish between the physical processes causing mixing in the atmospheric and oceanic boundary layers and relate them to mean properties of the layers.

(2) To examine and quantify aspects of the momentum and heat budgets in the atmospheric and oceanic boundary layers and the fluxes across and between them.

International Participation

Table 1 gives the prospective participation; the U.S.S.R. program is not definite. The number of groups given refers to distinct scientific projects, not number of scientists. Approximately half of the program is devoted to meteorological observations, and half to oceanography, with many of the projects strongly overlapping between the disciplines.

U.S. Participation

The U.S. participants are from eleven different laboratories, including academic institutuions, NOAA, and the U.S. Navy Postgraduate School. There is also some Navy scientific participation via satellite sensor validation and imaging.

Funding sources include ONR Code 480, the National Science Foundation through both its ocean sciences and atmospheric Sciences programs, NOAA, and NORDA Code 500. Also through the

NSF, the NCAR Electra research aircraft will participate, as will the R. V. Endeavour; the R. V. Atlantis-II is supported jointly by ONR Code 480 and the NSF Division of Ocean Sciences.

Current Status and Plans

Planning documents, including a complete set of Operations Plans, have been prepared and distributed, and ship and aircraft schedules are firm.

The field experiment will occur in three main phases from mid-July through mid-September 1978. There will be meteorological ships and buoys stationed at the corners of a 200 km-on-a-side triangle embedded in a larger area covered by oceanographic moorings. Roving hydrographic ships will continuously survey the larger area, and six to eight oceanographic ships will maintain work schedules in an intensive mooring zone in the middle of the meteorological triangle.

The site was chosen to maximize the chances for a sequence of strong meteorological inputs to the upper ocean, and the experiment is designed to observe both the inputs and the oceanic response to them.

Data workshops are scheduled beginning in the Spring of 1979, and a science workshop may be held in the Summer of 1980.

TABLE 1

PARTICIPATION IN JASIN 1978

COUNTRY	NO. OF SHIPS (SHIPS DAYS)	NO. OF AIRCRAFT (AIRCRAFT HRS.)	NO. OF PARTICIPATING GROUPS	NO. OF MOORINGS
AUSTRALIA	0	0	1	0
CANADA	0	0	2	0
DENMARK	0	0	1	0
F. R. GERMANY	3(129)	1(95)	13	12
IRELAND	0	0	1	0
NETHERLANDS	1(66)	0	2	½
U. K.	7(371)	1(100)	13	13½
U. S. A.	2(73)	1(105)	18	9
U. S. S. R.	1(60)	0	2	0
TOTALS	14(699)	3(300)	53	35

For more details concerning JASIN see Section V pp 8, 15, 16, 17, 23, 44, 56, 59, 66, 85, 106, 118.

MIXED LAYER EXPERIMENT (MILE)

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Long-Range Objective: The ultimate goal is to understand the physical processes governing the structure of the upper ocean so that for given atmospheric conditions one may accurately predict the future state of the upper ocean. Of particular interest is the deepening of the well-mixed layer during the passage of storms.

Objectives:

- To test and improve critical assumptions of mathematical models of the upper ocean.
- To determine time and space scales of the variability of temperature, velocity and salinity and the dependence of these scales on depth, atmospheric forcing and mean ocean structure.
- To describe the mechanisms and magnitudes of the transfer of momentum, heat and mass.
- To investigate the role of internal waves in determining oceanic structure.
- To improve our capability of making measurements in the upper ocean and to assess our methods by comparing different techniques.

Current Status. A cooperative experiment was conducted between mid-August and mid-September 1977 in the vicinity of Ocean Station P (50N,145W), about 600 miles west of Vancouver Island. Three ships participated in the experiment, the Canadian Weathership CCGS QUADRA, the USNS DE STEIGUER and the NOAA vessel OSS OCEANOGRAPHER. Three moorings were set for the measurement of currents, temperatures and surface waves. Shipborne observations of temperature, conductivity and velocity were made with vertically profiling and towed instruments. Observations of the large-scale temperature field were carried out by U.S. Navy and Canadian Forces aircraft which dropped AXBT's in the experimental area. Wind speeds during the experiment ranged from calm to 45 knots. Although ONR was the lead agency supporting the experiment, substantial contributions were made by Environment Canada, the Canadian Coast Guard, Canadian Forces, NOAA through the Pacific Marine Environmental Laboratory, the Naval

Oceanographic Office through the Military Sealift Command and the Pacific Patrol Wing of the U.S. Navy.

Accomplishments. During the most severe storm, wind speeds were in excess of 35 knots for 36 hours, causing the mixed layer to deepen from 20 to 40 meters. The observations during MILE are the most detailed ever obtained of an event of this type. Analysis of this event and the remaining observations is still in progress. However, a partial listing of the most significant preliminary conclusions can be given:

- There were large currents of inertial period (15.6 hr) throughout the experiment, with evidence of modulation by the wind.
- There were large internal waves in the upper thermocline of semidiurnal (12 hr) period throughout the experiment.
- Mean currents were small.
- The internal wave vertical displacements at the base of the mixed layer ranged up to 15 m.
- The horizontal wave length of the largest internal waves was approximately 5 km.
- Propeller type current meters appear to be less contaminated by noise at high frequencies than Savonius rotors.
- The intensity and frequency of occurrence of turbulent mixing during storms are much greater than during moderate or calm winds, although there are occasional turbulent patches at all times.

For more details concerning MILE see Section V pp 15, 19, 23, 38, 43, 45, 64, 76, 80, 85.

TITLE: NORPAX (The North Pacific Experiment)

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NORPAX is a multi-institutional research effort designed to investigate the dynamics of large-scale temperature anomalies in the upper ocean and to establish the connection between these anomalies and changes in climate over North America. It is expected that NORPAX results will assist in the forecasting of upper ocean thermal structure. Such forecasts might further be used in the prediction of atmospheric climate.

At the present time most of the NORPAX activities can be subdivided into three general groups: the Anomaly Dynamics Study (ADS), the Equatorial Dynamics Study (EDS), and the Atmospheric Climate Study (ACS).

The Anomaly Dynamics Study focuses on the several processes thought to be responsible for the development of large-scale, near-surface, thermal anomalies. Beginning with a working hypothesis that the most important process is the anomalous convergence or divergence of the Ekman surface drift, an extensive field experiment was mounted in the central mid-latitude North Pacific to test this theory. The field experiment consisted of long-term measurements of surface current by satellite tracked drogues, measurements of the thermal structure down to 500 meters and the calibration of existing U.S. Navy FNWC wind stress fields. By chance, the first year of the ADS field experiment happened to span the unusually severe winter of 1976-77. Data taken during that time indicates that weak vertical mixing at depth, below the traditional mixed layer and down to 300 meters or more, may be a much more important mechanism for generating anomalous thermal structure than Ekman divergence. However, evidence exists that below 300 meters a change in baroclinic structure does seem to correspond to the

Ekman pumping concept. One of the key questions raised from this experimental effort is how does weak mixing take place at such relatively great depths and how can a well defined surface mixed layer exist above it?

The ADS treats oceanic phenomena which are so large and so long lasting that classical ocean observation techniques by themselves are unfeasible. Research vessels, for example, cannot cover broad areas for the years necessary to adequately characterize the development of anomalies. Most research vessels are also unsuitable for cruising the open ocean and doing useful work during stormy seasons. The feasibility of collecting data for the ADS is based rather upon the use of new oceanographic tools, new statistical techniques for treating data and new operational arrangements. An excellent example of this new approach is the TRANSPAC component of the ADS. TRANSPAC uses commercial ships-of-opportunity to take about 500 XBT observations per month along the trade routes from the U.S. to Japan. Half of these ships are of Japanese registration. In addition to serving the scientific needs of ADS, TRANSPAC provides over 50% of the synoptic XBT data radioed into the U.S. Navy FNWC from the Pacific region. Soon to be implemented is a TRANSPAC extension into the equatorial Pacific between 20°S - 20°N (called EQUAPAC) involving French ships-of-opportunity in coordination with French scientists from the Office de la Recherche Scientifique et Technique Outre-mer (ORSTOM) in New Caledonia.

The NORPAX Equatorial Dynamics Study (EDS) focuses on the banded east-west current system that exists in the low-latitude Pacific. Immediate goals of the study are to describe the space and time variability of the currents and to design an experiment to investigate their dynamics. One of the early goals of the equatorial study was to assess the importance of mesoscale eddy dynamics at low latitudes. Progress toward this goal was made during the winter of 1977-78 when NORPAX scientists performed their first large field experiment in the tropics. Eight long-range P-3 aircraft, provided by the U.S. Navy Reserve, the Naval Oceanographic Office and NOAA, dropped AXBTs to obtain frequent temperature sections between Hawaii and Tahiti. In addition, two research vessels did hydrographic measurements, launched upper air balloons and deployed a variety of moored and floating instruments. Preliminary results indicate that the strong North Equatorial Countercurrent is relatively steady on a monthly time scale while the region closer to the equator is contaminated by mesoscale eddies. A second and much larger NORPAX field experiment in the mid-equatorial Pacific is scheduled for the FGGE (First

GARP Global Experiment) year, 1979. One major question to be addressed at that time is the relative importance of locally forced phenomena versus disturbances which are propagated into the region from the far field.

A third component of NORPAX, the Atmospheric Climate Study (ACS), is designed to investigate ocean/atmosphere interaction on climatic time scales. Scientists working in this area use large historical data bases to develop statistical/phenomenological models of the response of the atmospheric circulation to sea surface temperature anomalies. Using these techniques NORPAX scientists were able to forecast the general patterns of surface temperatures in the U.S. during the winters of 1976-77 and 1977-78.

At the present time, NORPAX consists of about 35 Co-Principal Investigators working at 19 educational institutions and government laboratories. The main sources of support are the Office of Naval Research and the National Science Foundation's Office of the International Decade of Ocean Exploration (IDOE). In addition to these sources some individual NORPAX investigators are subsidized by the Naval Ocean Research and Development Activity (NORDA), the U.S. Navy Fleet Numerical Weather Central (FNWC), the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA). Foreign NORPAX participants from Germany, France, England and Japan are supported mostly by their own governments.

For more details concerning NORPAX see Section V pp 5, 22, 23, 31, 47, 49, 57, 69, 74, 76, 119.

POLYMODE

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POLYMODE is an international cooperative scientific investigation of low-frequency, medium scale motions in the sea. Its ultimate purpose is to establish the dynamics and statistics of mesoscale motions, their energy sources, and role in the general circulation of the ocean.

By the early 1970s, eddies, oceanic mesoscale variabilities with horizontal scales of the order of 100 kilometers and time scales of the order of 60 days, had emerged as a dominant factor in the medium frequency processes in the ocean. The basic long-range goal of eddy science is to understand the dynamics of eddies and their role in the large scale circulation in the oceans. As a major mechanism in the energetic processes of the ocean, eddies may have strong influences in the areas of meteorology, distribution of chemical properties in the ocean, and marine biology.

POLYMODE builds on results from two previous large scale intensive eddy experiments conducted in this decade. Limited POLYMODE experimentation began in 1975. The intensive field work phase is from mid-1977 to mid-1978, with some additional work being carried out through 1979.

US efforts in POLYMODE are being carried out under a bilateral agreement with the USSR, and in conjunction with related work being done by oceanographers from Canada, the United Kingdom, France, and the Federal Republic of Germany. The Canadian and European work is coordinated through SCOR Working Group 34.

The US work is funded by the National Science Foundation (Office of the International Decade of Ocean Exploration) and the Office of Naval Research. The National Oceanic and Atmospheric Administration of the Department of Commerce administers the US/USSR bilateral agreement and provides support for POLYMODE. Continual liaison is maintained with these agencies and with the Office of the Oceanographer of the Navy.

The experimental program of POLYMODE is divided into two areas: statistical-geographical exploration, and local dynamics. These areas are complementary, and are being carried out simultaneously and with some overlap in space.

The statistical-geographical work is aimed towards determination of the geographic occurence and variability of eddies in the North Atlantic Ocean. Arrays of moorings have been set by the US on either side of the Mid-Atlantic Ridge and in the North Equatorial Current, by the USSR on the Hatteras Abyssal Plain, by Canada in the Gulf Stream Extension region, and by a UK/France/FRG group in the northeastern basin of the Atlantic. Each of these arrays has now been in place for a year or more.

The local dynamics work is designed to closely examine one or more eddies for a shorter time in one location, and to provide a quantitative picture of the physical processes involved and the dynamics of the eddy. An intensive experiment will be deployed in May-July 1978 on the Hatteras Abyssal Plain in conjunction with the USSR statistical/synoptic array already in place there. The US mooring array and SOFAR float array associated with this experiment will remain in place for a year after the intensive experiment, thus contributing to the statistical-geographical objectives.

Theoretical efforts in POLYMODE include modelling of eddy processes and the comparison of modelling results with field observations. A number of theoretical and modelling efforts are in progress both within the US and in cooperation with the USSR.

POLYMODE is approaching the end of its major field work phase. It is anticipated that analysis and interpretation of the results will take place in 1978-1979, and, in a more general way, into the 1980s.

The exchange and interpretation of data in POLYMODE will take place on several levels. All data will eventually be archived in the World Data Center. Both formal and informal arrangements exist between the US and the USSR for data exchange, and some exchanges on both levels have already occured. Arrangements with Canadian, French, FRG, and UK participants are less formalized, but already active.

Data from the early POLYMODE field work has already modified our picture of eddy occurence and processes in the ocean. Several distinct types of eddies have been identified, perhaps characteristic of different regions of the ocean.

The USSR synoptic mooring array and US/USSR synoptic XBT surveys on the Hatteras Abyssal Plain have provided a unique picture over a period of ten months (to be over a year upon completion of the experiment) of the eddy activity in this region. They show high eddy activity, interaction between eddies, and confirm a generally westward movement of the individual eddies.

For more details concerning POLYMODE see Section V pp 23, 31, 32, 43, 64, 94, 97, 100, 108, 110, 126.

a. VARIABILITY IN SOUND TRANSMISSION THROUGH THE OCEAN INTERIOR

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b. We will study, by observation and theory, the role of ocean processes (internal wave-induced temperature fluctuations and currents, intrusions and associated finestructure, mesoscale eddies, ...) in determining the variability of sound transmission through the ocean's interior. The goals are (i) to contribute to our understanding of the fundamental limits on signal coherence (space and time) in the ocean environment, and (ii) to work towards the inverse problem of monitoring the oceans by acoustic means.

c. The objectives of the program include:

(i) To study the transition from unsaturated to saturated acoustic forward scattering, taking advantage of a diversity of frequency, range, and paths under a simple ocean geometry.

(ii) To separate the acoustic role played by different ocean processes.

(iii) To measure deterministically features whose scales are large as compared to the transmission path.

(iv) Recording of the 220 Hz source at a California coastal station for use in large scale monitoring (ocean acoustic tomography).

d. Evaluation of data obtained in a recent field experiment (April 1978) is now getting underway. Although there were significant equipment failures, we have some useful acoustic measurements. In particular, some interesting records obtained at a coastal station are encouraging with respect to a future ocean acoustic tomography program.

Robert Spindel (WHOI) is collaborating in this study; in addition to his own 220 Hz sound transmission measurements, he is taking responsibility for position-keeping (monitoring tethered capsules) and for the deployment and retrieval of moorings. Charles Cox (SIO) and Eli Katz (WHOI) made supplemental environmental measurements on the WECOMA and Robert Bernstein (SIO) contributed satellite imagery and AXBT surveys.

e. During the two preceding years we have worked on the reciprocal sound transmission between two vessels (Worcester, in press). The experiments have demonstrated that the mean sound velocity and the mean current component along the acoustic path can be measured with great precision. Further, the statistics of pulse spreading and wandering was not inconsistent with the statistics derived by Dashen for an internal wave model (Flatté *et al.*, in press).

For more information concerning Variability in Sound Transmission see Section V pp 6, 20, 61.

SECTION IV---INDIVIDUAL PROJECTS BY INSTITUTION

University of California, Berkeley

Watson, K.M.: Transfer of Energy Among Modes Within the Oceanic Internal Wave Field

University of British Columbia

Burling, R.W. and Pond, S.: Measurement and Parameterization of Air-Sea Fluxes at High Wind Speeds; Adaptation of Bulk Parameterizations to allow Flux Computations from Climatological and Synoptic Data

Miyake, M.: The Upper Ocean Response Study

Osborn, T.R.: Studies of Microstructure

University of Cambridge

Gill, A.E., Anderson, D.L.T., and Killworth, P.D.: Ocean Modelling Newsletter

The Catholic University of America

Ling, S.C. and Kao, T.W.: Study of the Mechanics of Momentum, Water Droplets, Moisture, and Heat Transfer at the Sea-Air Interface Under High Sea States

University of Delaware

Garvine, R.W.: Theoretical Study of Oceanic Frontal Dynamics and Thermodynamics

Mooers, C.N.K.: Primer on Oceanic Fronts

Fleet Numerical Weather Central

Hughes, R.E.: Continuation of the NORPAX Ship of Opportunity Program

Florida State University

O'Brien, J.J.: Research in Mesoscale Atmosphere and Ocean Interaction Ocean Forecasting

Sturges, W.: Studies of Ocean Circulation

Weatherly, G.L. and Blumsack, S.L.: Studies of the Oceanic Bottom Boundary Layer

Harvard University

Robinson, A.R.: Dynamics of Oceanic Motions

University of Hawaii

Harvey, R.R.: Equatorial Circulation Study

Magaard, L.: Analytical Modelling of the Large-Scale Temperature Fluctuations in the North Pacific

Institute of Oceanographic Sciences

Gould, W.J.: XBT Sections in the Northeast and South Atlantic

Lamont-Doherty Geological Observatory

Gordon, A.L.: Sea Level and Sea Surface Temperature Expressions of Ocean Transients as Viewed from Satellite

Max-Planck Institut für Meteorologie

Hasselmann, K.F.: Computations of the Nonlinear Energy Transfer in a Gravity-Wave Spectrum

University of Miami

Bleck, R.: Numerical Modeling of Ocean Front Dynamics

Brown, O.B.: Satellite Remote Sensing of Large-Scale Oceanic Transient Events

Duing, W.: Transient Processes in Ocean Currents

Rooth, C.G.H.: Frontal Dynamics on Seasonal Time Scales (Previous Dynamics of Seasonal Variability)

Schott, F.: Analysis of Mid-Ocean Circulation

Schott, F.: Currents at Ocean Boundaries

Massachusetts Institute of Technology

Mollo-Christensen, E.: Oceanographic Uses of Satellite Information

Stommel, H.M. and Regier, L.: Mapping the Horizontal Structure of Near-Surface Currents During the POLYMODE Local Dynamics Experiment

Wunsch, D. and Eriksen, C.C.: Internal Waves, Equatorial Dynamics and Acoustic Tomography

Pacific Marine Environmental Laboratory

Halpern, D.: Mesoscale Ocean-Atmosphere Response Studies During the 1978 Joint Air-Sea Interaction (JASIN) Experiment

Halpern, D.: Variability of Wind-Generated Upper Ocean Currents During the Mixed Layer Experiment (MILE)

Hayes, S.P.: Response of the Upper Ocean Hydrography to Winds

Naval Ocean Research and Development Activity

Holyer, R.J.: Ocean Water Color Satellite Utilization Experiment

La Violette, P.E.: Definition of Ocean Surface Current Boundaries Using Synthetic Aperture Radar over the Tail of the Grand Bank

Naval Postgraduate School

Elsberry, R.L. and Garwood, R.W., Jr.: Oceanic Thermal Response to Atmospheric Forcing

Haney, R.L.: Numerical Studies of the Dynamics of Large Scale Ocean Anomalies

Jung, G.H.: Low Wavenumber Ocean Energy Transport

University of North Carolina/North Carolina State University

Bane, J.M., Jr. and Brooks, D.A.: Observations of Topographic Rossby Waves and Gulf Stream Meanders Along the Continental Slope

Nova University

Brooks, I.: Studies of Flow Through the Passages of the Lesser Antilles

McCreary, J.P. and Moore, D.W.: Studies of Equatorial Dynamics

Moore, D.W.: Studies of Equatorial Dynamics

Spillane, M.: Time-Dependent Stratified Flow Over Sloping Bottom Topography

Oregon State University

Burt, W.V.: Mixed Layer and Seasonal Thermocline Studies, Participation in JASIN-77 and Preparation for Participation in JASIN-78

Caldwell, D.R.: Mixed-Layer Microstructure

de Szoeke, R.A.: Dynamics of the Ocean Surface Mixed Layer

Niiler, P.P.: Hydrodynamics of the Ocean Surface Layers

Paulson, C.A.: Air-Sea Interaction

University of Rhode Island

Rossby, T. and Dorson, D.: SOFAR Float Program

Wimbush, M.: The Relation of Sediment Movement to the Benthic Current Flow in the Florida Straits

Science Applications, Inc.

Lambert, R.B., Jr.: Ocean Mixing Processes

Scripps Institution of Oceanography

Barnett, T.P.: Thermal Structure Monitoring and Modeling in the North Pacific Ocean

Bernstein, R.L.: Merging Satellite and Conventional Oceanographic Data to Explore North Pacific Mesoscale Circulations

Cox, C.S.: Small Scale Oceanic Processes

Cutchin, D.L.: NORPAX Program Administration

Davis, R.E.: Upper Ocean Dynamics

Gibson, C.H.: Measurements of Velocity, Temperature and Conductivity Fluctuations During the Mixed Layer Experiment (MILE) by a Towed Ocean Profiling System - Data Analysis

Knox, R.A.: Observations and Analyses of Indian Ocean Equatorial Currents

Lange, R.E.: Small Scale Oceanic Features

McNally, G.J.: Satellite-Tracked Drifting Buoys

Pinkel, R.: Dynamics of the Upper Ocean Internal Wave Field

Reid, J.L.: World Ocean Circulation: South Argentine Basin, Weddel Sea and Atlantic Indian Basin

Stewart, R.H.: Radio Measurements of the Sea Surface

White, W.B. and Bernstein, R.L.: Study of the Dynamics of Large-Scale Thermal Variability in the Upper Waters of the Mid-Latitude North Pacific

The Sippican Corporation

Tirrell, B., Reed, E., Calianno, C., and Dugan, J.: Feasibility Study for Improving the AN/SSQ-36, The Navy's Airborne Expendable Bathythermograph (AXBT)

University of Southern California

Browand, F.K.: Turbulent Decay: Laminar-Turbulent Interfaces

Maxworthy, T.: Turbulent Decay: Dynamics of Rotating and Non Rotating Intrusions and Internal Solitary Waves

Stanford University

Peterson, A.M. and Vesecky, J.F.: Ocean Wave Measurement by Analysis of Radar Images of the Ocean

Howard, H.T.: Radio Measurements of the Sea Surface

Texas A & M University

Elliott, B.A. and Merrell, W.J., Jr.: Regional Studies in Physical Oceanography

Emery, W.J.: Dynamic Topography from Temperature Maps: A Monitor of Ocean Circulation Changes

Emery, W.J. and Dugan, J.P.: XBT Swath Analysis, A Study of Spatial Variability

Ichiye, T.: Entrainment Processes at Ocean Fronts

Reid, R.O.: Numerical Modelling

Spence, T.W.: The Dynamics of Cyclonic Gulf Stream Rings

Vastano, A.C.: Kuroshio Tracking Experiment

Vastano, A.C.: Cyclonic Ring Experiment

University of Washington

Businger, J.A. and Katsaros, K.B.: Air-Sea Interaction Processes

Desaubies, Y.J.F.: Investigation of Internal Wave Dissipation and Small Scale Temperature Structure in the Ocean

Gregg, M.C.: Small Scale Mixing Processes

Roden, G.I.: Oceanic Fronts of the Central Pacific Ocean

Woods Hole Oceanographic Institution

Armi, L.: Benthic Boundary Layer Experiment

Briscoe, M.G.: Internal Waves

Bruce, J.G. and Warren, B.A.: Temperature Measurements with XBT's in the Northwestern Indian Ocean

Fofonoff, N.P.: Potential Density, Energy and Vorticity Computations

Fofonoff, N.P., Schmitz, W.J., Jr., and Luyten, J.R.: Moored Array Program

Hogg, N.G.: Island Trapped Waves

Joyce, T.M.: Internal Wave and Mediterranean Water Front Studies

Katz, E.J.: Current Shear Across an Oceanic Front

Luyten, J.R.: Equatorial Jets in the Indian Ocean (INDEX)

McCartney, M.S.: Thermostadal Analysis of the Upper Water Masses and Circulation of the World's Oceans

Rhines, P.B.: Western-Boundary Undercurrent

Richardson, P.L.: Cyclonic Gulf Stream Rings

Sanford, T.B.: Oceanic Variability and Dynamics

Schmitz, W.J., Jr.: Low-Frequency Large-Scale Ocean Circulation

Schmitz, W.J., Jr. and Hogg, N.G.: Currents in the Charlie-Gibbs Fracture Zone (CGFZ)

Voorhis, A.D.: Oceanic Fronts

Warren, B.A.: Large-Scale Circulation

Webb, D.C. and Gould, W.J.: Development of a Towed, Two Component Surface Current Sensor

Williams, A.J., 3rd: Salt Fingers and Microstructure

Williams, A.J., 3rd: Velocity Structure of Boundary Layer Flows

Worthington, V.: Water Mass Formation and Gulf Stream Variations

SECTION V---INDIVIDUAL PROJECT SUMMARIES

Summaries of individual research projects are given on the following pages, alphabetical according to the name of the senior principal investigator.

Benthic Boundary Layer Experiment

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Long-rang objectives. A description and maybe some understanding of deep ocean turbulence and mixing processes; the identification of the dominant mechanisms responsible for the distribution and mixing of deep water types. Primary focus has been on the bottom boundary layer as a source of turbulence capable of cross-isopycnal mixing. When coupled with horizontal along-isopycnal advective and diffusion processes, the products of bottom boundary layer mixing are exchanged with the interior and may be the dominant source of deep ocean microstructure and the primary large scale mechanism responsible for vertical mixing in the deep ocean.

Project objectives. A detailed description and understanding of bottom mixed layer structures and dynamics with attention to mesoscale and internal wave variability.

Status of project and accomplishments. The field exploration of the benthic boundary layer on the Hatteras Abyssal Plain was successfully completed in late August 1977. A temporal description was provided by an array of current meters and temperature sensors spanning the bottom mixed layer. A spatial description was obtained using a towed yo-yo-ing CTD nephelometer profiler in conjunction with real time acoustic navigation.

Analysis of this data has shown the occurrence of intrusive layers (Armi, 1978) and large scale patchiness with a scale of $\sim$ 7-10 kms. Similar advected temporal variability as well as superposed internal wave fluctuations can be seen in the moored array records (Armi, 1978. Mixing in the deep ocean — the importance of boundaries, Oceanus, 21 (1), 14-19).

A description of along isopycnal horizontal advection and/or diffusion of anomalies in potential temperature, salinity and particulate matter for Denmark Straits Norwegian Sea Overflow Water is included in Armi (1978) with an estimate of vertical mixing due to boundary generated turbulence.

1. a. Observations of Topographic Rossby Waves and Gulf Stream Meanders along the Continental Slope.

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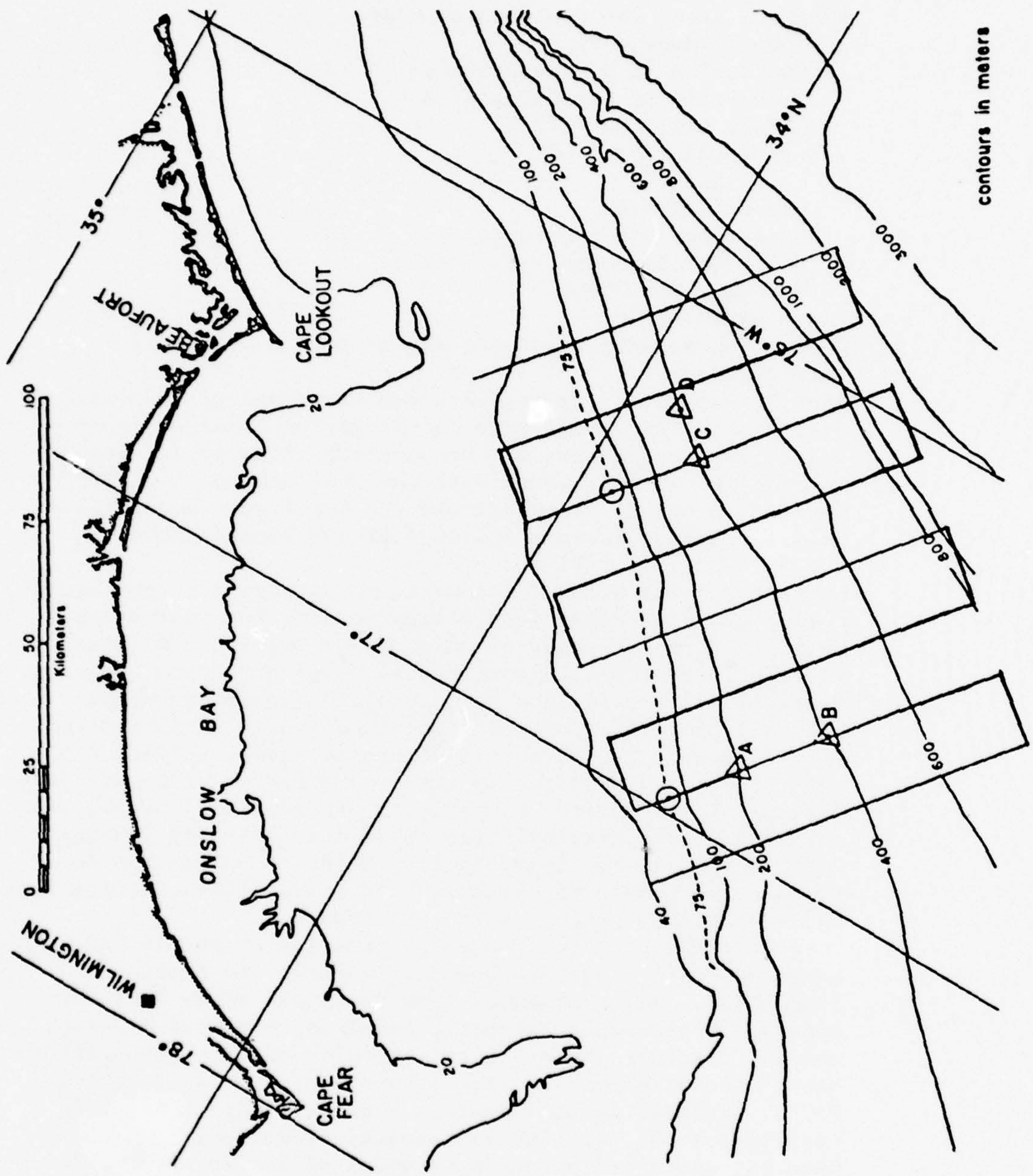
b. Long-range scientific objectives of the co-principal investigators.
John M. Bane Jr.: To increase our knowledge of long wave dynamics in the ocean, with particular emphasis on generation, energy transfer and propagation, dissipation, and interaction of long waves with the Gulf Stream.
David A. Brooks: To understand the important mechanisms driving Florida Current and Gulf Stream fluctuations in the South Atlantic Bight.

c. Current, temperature and conductivity data will be collected during two four-month long mooing periods to examine the detailed structure and time history of current and density fluctuations along the continental slope off North Carolina. Vertical and cross-slope structure and alongshore propagational properties of the fluctuations will be determined. Correlation of the current and density data with wind data, and comparision of directly measured currents with satellite imagery of sea-surface temperature patterns will be done to investigate the possibilities of wind or lee-wave forcing. Field data will be compared with theory to assess the importance of stable topographic Rossby wave (TRW) propagatigation and instability processes in the Stream.

d. Current project status: Numerical studies of stable TRW propagation in a western boundary current are nearing completion. Major equipment for the field study (current meters, thermographs, acoustic releases) has been ordered, and the first cruise has been scheduled on the R/V ENDEAVOR.

e. Major accomplishments: Brooks' model of stable barotropic TRW's propagating in a western boundary current has been adapted for the Carolina continental slope/shelf region. Bane has developed a two-layer model of stable baroclinic TRW's propagating in a baroclinic western boundary current, and work on a continuosly stratified baroclinic TRW model is underway.



Experiment area showing mooring locations (triangles) and ship/aircraft tracks for hydrographic measurements. (Circles are locations of current meter moorings that are part of a North Carolina State University shelf circulation study.)

THERMAL STRUCTURE MONITORING AND MODELING IN THE NORTH PACIFIC OCEAN

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Long Range Objectives: Describe and explain the large-scale space/time variability in the near surface temperature field of the central Pacific Ocean. If possible, develop a statistical dynamical model for prediction of the observed thermal structure variability. These objectives relate to the Navy requirements for long range environmental predictions that affect all aspects of Naval operations and the statistical description and prediction of the major source of variability in the near surface sound velocity field.

Program Objectives: The program objectives are: (1) Describe quantitatively the large-scale seasonal temperature fluctuations that occur in the upper 300 meters of the central Pacific Ocean. (2) Attempt to explain, or at least put order of magnitude limits on the physical processes that are causing the fluctuations. (3) Develop stochastic model to predict the near surface, large-scale temperature fluctuations.

Current Status: (1) The AXBT flights ended in April 1977. A two and one-half year record of almost monthly sections was obtained. These data include sections through the extremely anomalous ocean/atmosphere events of 1976-77. (2) In spring 1977, it was discovered that the Magnavox AXBTs had a serious time constant problem. The problem was so severe that the data from these instruments would be virtually useless without correction. An oceanographic cruise and series of laboratory experiments were carried out to compute the necessary response function of the AXBTs so that the data mentioned above could be corrected. With correction, the AXBTs are good to an accuracy of approximately $\pm 0.3^{\circ}C$. (3) The response function has been used to correct all of the BT traces obtained during the course of the experiment. (4) The space and time scales of the observed temperature variability have been computed and are being prepared for publication. (5) Estimates of air-sea heat exchange, Ekman pumping, and meridional advection are being computed for the 30 month duration of the experiment.

Major Accomplishments - 1976-77: (1) Discover and define the thermal lag problem associated with Magnavox AXBTs. (2) Develop a transfer function to correct the problem. (3) Correct the entire AXBT data set obtained during this program. (4) Compute the space and time scales of the temperature anomaly field observed during the 30 months of the experiment.

Title: Merging satellite and conventional oceanographic data to explore North Pacific mesoscale circulations

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Long range scientific objectives: application of satellite remote sensing information to improve description and understanding of ocean circulation.

Project objectives: integrate available satellite infrared scanner data with ship hydrocast, aircraft AXBT, current meter mooring and surface drifter data to define mesoscale eddy features occurring along the west coast of the U.S. Emphasis is on determining the processes that initially generate eddies, and then follow them as they propagate away from the generating areas.

Current project status: the principal investigator is presently being assisted by an experienced satellite meteorologist, Robert Whritner, and a graduate student, Mike Van Woert, in assembling the above mentioned data sets. So far these include: (i) monthly hydrographic surveys of the California Current system, covering December 1977 to November 1978; (ii) three air XBT surveys at ten day intervals in March/April 1978 off Southern California. The surveys, which are performed by Navy P-3C aircraft under PATWINGSPAC Moffett Field, are also in support of an extensive acoustic experiment headed up by Walter Munk. (iii) DMSP and NOAA infrared scanner data. The DMSP data is acquired through close cooperation with the Navy Weather Service NAS North Island, in San Diego.

Initial examination of all three data sets shows excellent consistency with strong mesoscale circulation features present.

Numerical Modeling of Ocean Front Dynamics

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Long-Range Scientific Objectives

Numerical simulation of the life cycle of baroclinic disturbances (meanders, eddies) embedded in oceanic western boundary currents, with special emphasis on frontogenetical processes. Application of Numerical Weather Prediction technology to the deterministic prediction of oceanic circulation events.

Objective of the Project

Development of a multi-level ocean model using density as vertical coordinate. Application of this model to studies of the seasonal variability of the Somali Current, especially the upwelling associated with the establishment of the Somali Current front. The principal advantages of an "isopycnic" ocean model are: (a) its ability to improve grid resolution in regions where fronotogenesis takes place; and (b) the elimination of cross-isopycnal mixing found in cartesian coordinate models.

Current Status

The numerical technique has been tested in a coastal upwelling experiment in which an idealized square ocean basin with flat bottom and vertical sidewalls is subjected to an anticyclonic wind stress. The model is presently being adapted to run on an in-house, ONR-sponsored PDP11 computer. Basin configurations (including bottom topography) representing the Arabian Sea will be introduced next.

Internal Waves

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Long-Range Objectives

Understanding of the role played by internal gravity waves in the transfers of energy, momentum, heat and mass vertically and horizontally in the ocean. Determination of the sources and sinks of internal wave energy, and the relation of internal waves to larger-scale (especially fronts and eddies) and smaller-scale (especially finestructure) ocean processes.

Project Objectives

Present work is devoted to an exploration of the energy balance of internal waves in the upper ocean via field work during the international Joint Air-Sea Interaction project (JASIN). The experiment will, in cooperation with other U. S. and foreign investigators, monitor the fluctuations of atmospheric and upper-ocean generating mechanisms for internal waves, the changing spectra of the internal waves themselves, and the finestructure field associated with energy losses from internal waves. Together with theoretical and numerical analyses, we expect to obtain a description of upper-ocean internal-wave space-time variability as well as the main objective of assessing the energy balances.

Status of Project and Accomplishments

JASIN will occur during July-September 1978. The planning is complete and engineering preparations are in progress. Part of my effort has been to coordinate the U.S. program for JASIN; this has gone well, partly because several of the U.S. participants will operate from the R. V. Atlantis-II in cooperation with this investigator.

One wrap-up accomplishment was the issuance of W.H.O.I. Technical Report No. 78-10, a final report on the Internal Wave Experiment (IWEX); it contains a bibliography of all articles pertaining to IWEX during 1973-1977, and a copy of the inverse analysis report produced in Germany by Willebrand, Olbers, and Müller. A journal article based on that report appeared in Journal of Geophysical Research in January, 1978. The IWEX project was unique in that international collaboration existed at both the planning and analysis stages without the necessity for specious joint authorship of each document.

STUDIES OF FLOW THROUGH THE PASSAGES OF THE LESSER ANTILLES

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The long range scientific objective of the principal investigator is to understand the evolution of the Florida current. Work towards this goal include dropsonde experiments across the Florida Current at Key West and Miami, a mini-buoy experiment in the Caribbean Sea and this dropsonde experiment in the passages of the Lesser Antilles.

The objective of this project is to measure the inflow to the Caribbean Sea. It is believed that the majority (80%) of the Caribbean waters enters through three passages in the Lesser Antilles. This experiment attempts to test this belief while also determining the characteristics of the incoming water.

The field work in the St. Lucia Passage was successfully completed in the summer of 1977. Analysis of this data is progressing presently.

The average transport through the St. Lucia Passage was significantly lower than previously believed.

TURBULENT DECAY - Subtitled - Laminar-Turbulent Interfaces - F. K. Browand, University of Southern California, Department of Aerospace Engineering, Los Angeles, California 90007, (213) 741-2035.

b) To contribute to a fundamental understanding of turbulent flows, and to apply this understanding to oceanic mixing processes.

c) To identify the most important features of turbulent mixing in the ocean (at smaller scales) by means of detailed laboratory studies.

d) We have previously made a detailed series of measurements of turbulence produced by shear at the boundary between two layers of different density. A paper on this subject has been submitted for publication. The work will continue in a larger facility completed recently with the following objectives: i) to observe mixing at more realistic Reynolds numbers; ii) to study the wave field produced by the mixing event.

We are also studying the structure of the homogeneous, turbulent mixing layer. Our goals in the intermediate future are: i) to use acoustic forcing to study the interactions of the large scale features; ii) to determine the spanwise (cross flow) extent of these large scale features.

e) The turbulence produced by shear at the boundary between two layers of different density consists of several reasonably distinct phases (figure 1): i) the actively turbulent growth region, characterized by large vortical structures or "billows"; ii) the collapse region, where wave production occurs; iii) the turbulent decay region, which leaves "fossil" density structure and waves. Almost all the molecular mixing occurs in (ii) and (iii).

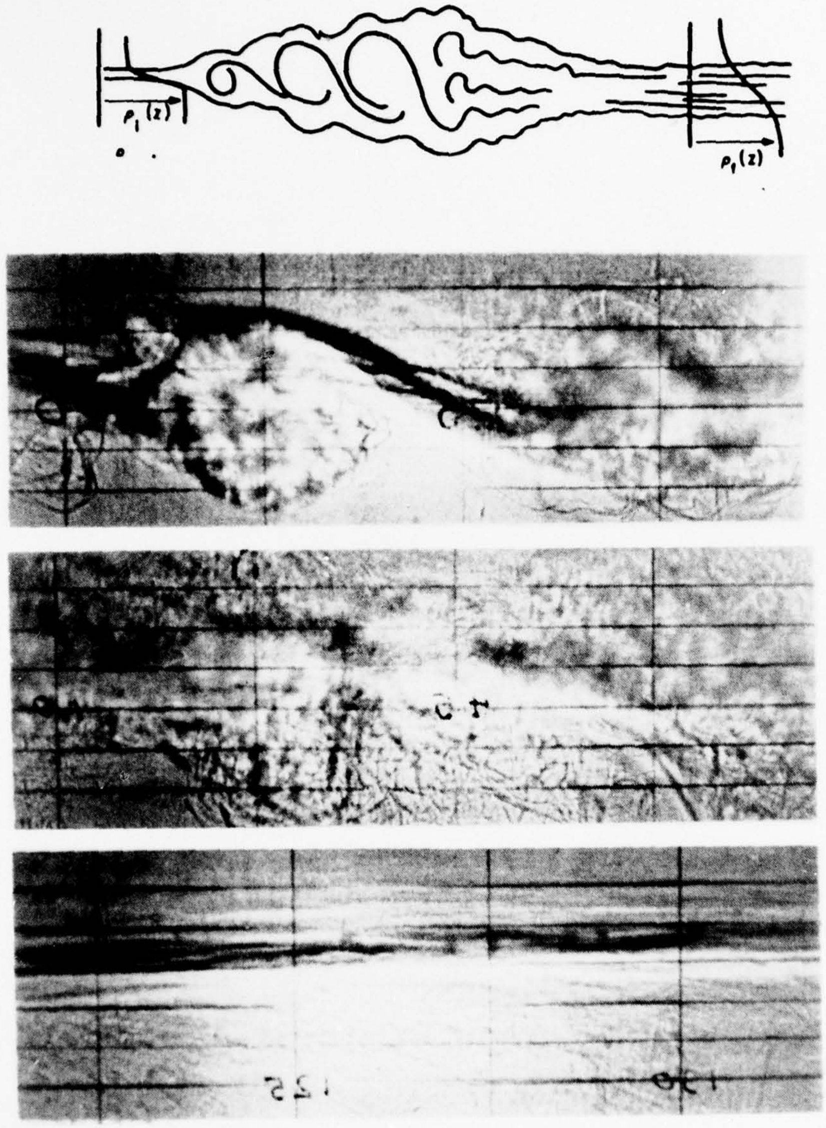

Fig. 1. The mixing event in a stratified fluid with shear. Photographs correspond to the three regions depicted above: i) actively turbulent; ii) collapse; iii) turbulent decay, leaving "fossil" density structure.

SATELLITE REMOTE SENSING OF LARGE-SCALE OCEANIC TRANSIENT EVENTS

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LONG-RANGE SCIENTIFIC OBJECTIVES

Develop quantitative methods for the interpretation of satellite-sensed sea surface temperatures and wind speed. In particular, apply these types of synoptically sensed data to the problems of western boundary current spinup, equatorial current meandering, and large-scale mixed layer heat budgets.

PROJECT OBJECTIVES

Develop simple algorithms suitable for mini-computer use which will extract, calibrate and map raw satellite data and insert it into an accessible data base.

Study the large-scale thermal response of the equatorial Atlantic Ocean during GATE, with the specific objectives of identifying the spatial and temporal scales of the wavelike motions of the South Equatorial Current.

Study the large-scale thermal response of the Western Indian Ocean to the Southwest Monsoon. Specifically, determine the role of large-scale vs. local wind forcing on the initial spinup.

Study the genesis of the surface thermal signature of the"Great Whirl", the large-scale anticlonic eddy southeast of Socotra, during Somali Current spin up. Identify principal mechanisms responsible for large-scale cooling in the interior of the Western Indian Ocean. Investigate the causes of the variability of the Somali Current separation latitude.

CURRENT STATUS

Satellite data processing is presently carried out in several stages:

1. Scanning Radiometer (SR) data from Indian Ocean is being routinely processed and analysis is underway.
2. Polar orbital navigation model (based on orbital emphemeris) in final testing.
3. Both USAF/DMSP and NOAA/VHRR infrared data from the East African coast are being archived on magnetic tape.
4. VHRR rubber mapping algorithm near completion.

MAJOR ACCOMPLISHMENTS

1. GATE result: observation of long wave meander of the South Equatorial Current.
2. GATE result: identification of time and space meanders of zonally mapped propagating waves in satellite derived SST.
3. Indian Ocean: identification of bimodal structure of the Somali Current.
4. Indian Ocean: monsoon induced large scale cooling of Western Indian Ocean.

TEMPERATURE MEASUREMENTS WITH XBTs IN THE NORTHWESTERN INDIAN OCEAN

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Our long-range scientific objectives are to understand the response of the western Indian Ocean to the monsoon winds, particularly that of the dominant southwest monsoon. We hope to determine the rate of build-up of the circulation, the variation during a season and also from year to year, whether certain preferred modes exist in the current patterns (i.e., does the large eddy occurring off the Somali coast during the southwest monsoon and its associated eddies become arranged in recognizable or predictable ways from one year to the next), the decline of the flow upon cessation of the monsoon winds, the changes in the heat content in the mixed layer, the variations in the region of upwelling off the Somali and Arabian coasts, and the changes occurring in near-equatorial dynamic topography as a result of the Somali circulation. Because of the large changes that occur in the strong horizontal gradients in the mixed layer (see figure 1) knowledge of this region might be of particular importance to the Navy, especially from an acoustic standpoint.

The objective of the project at present is to obtain a time series of temperature sections from XBTs set from tankers along the sea lane off the Somali and Arabian coasts. The sections pass fortuiously through the region of the large eddies which develop in the Somali Basin during the southwest monsoon and allow excellent monitoring of the development and decay of the eddies.

At present we have been able to follow the monsoon eddy circulation for two complete southwest monsoons and plan to continue the program through the 1979 period of intensive oceanographic study in the Somali current domain.

Our major accomplishments to date have been to show that for each southwest monsoon in 1975, 1976, and 1977 the general eddy configuration once formed at the commencement of the southwest monsoon appears to remain over the duration of the monsoon. We have found in all of our past measurements that one of two basic configurations tends to occur. Also we were able to monitor the 1975 eddy throughout the succeeding northeast monsoon and see evidence that it may have continued into or influenced the early stages of the next year's southwest monsoon. It is not clear however that the 1976 eddy was able to last into 1977. We have also found the equatorial near-surface water to have been cooled considerably by the 1976 eddy circulation, thus possibly modifying the equatorial currents in this region.

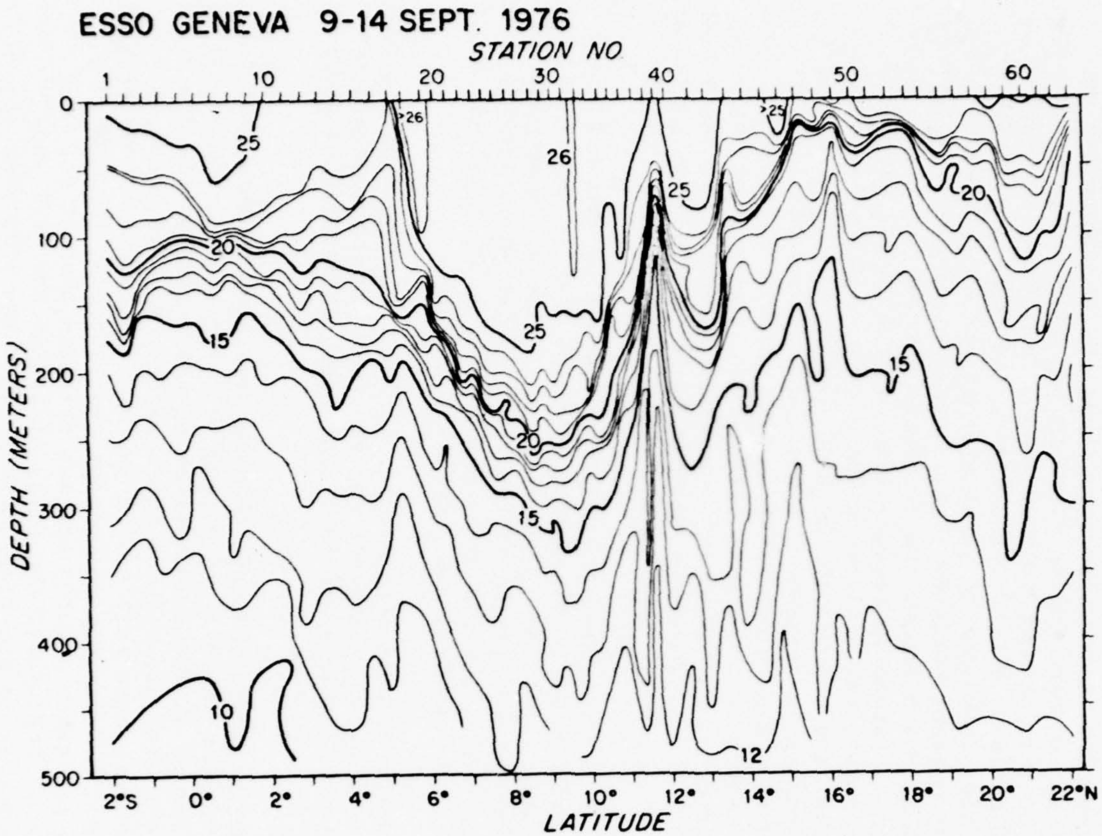

Figure 1. Temperature section, °C, from XBT stations along tanker track from 2° S, 48° E to 22° N, 61° E off Somali and Arabian coasts. Fully developed Somali "prime" eddy occurs between 5°N - 12°N. Weaker southern eddy south of 5°N.

MEASUREMENT AND PARAMETERIZATION OF AIR-SEA FLUXES AT HIGH WIND SPEEDS; ADAPTATION OF BULK PARAMETERIZATIONS TO ALLOW FLUX COMPUTATIONS FROM CLIMATOLOGICAL AND SYNOPTIC DATA

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The long-range objective is to understand the nature, mechanisms and consequences of air-sea processes. Knowledge of the transfers is of importance to meteorological and oceanological forecasting. Momentum transfer is important for waves and currents and the mixing of the upper layer. The total energy flux determines the formation and breakdown of the seasonal thermocline. The forecasting of these phenomena is important in many practical ways, e.g. navigation, operations, submarine detection, ship motions, etc. Oceanic and atmospheric turbulence are important in diffusion of materials, wake detection and radio transmission scatter.

The objectives are: (1) to measure and parameterize fluxes of momentum, sensible heat and latent heat (moisture) up to high enough wind speeds to allow good calculations of these fluxes over the ocean; (2) to see if a wider range of data may be used by comparing fluxes calculated from data reduced to climatological form (wind roses and averages of air-sea temperature and humidity differences) and synoptic form (surface pressure maps and air-sea temperature and humidity differences averaged over various periods) with fluxes calculated using bulk aerodynamic formulae.

Many data allowing momentum and sensible heat flux estimates by both Reynolds flux and dissipation methods in winds up to 20 ms^{-1} have been collected on the Bedford Institute Stable Platform located about 10 miles off Halifax, Nova Scotia. In the 15 - 20 ms^{-1} range of wind speed, 45 Reynolds flux and 85 dissipation estimates of C_D under unlimited fetch conditions may be made; there are many more unlimited fetch data at lower speeds and many limited fetch data. Preliminary analysis shows that the drag coefficient increases somewhat with wind speed and is basically in agreement with the Smith and Banke formula ($10^3 C_D = 0.63 + 0.066\ U_{10}$, U_{10} in ms^{-1}). The Reynolds flux and dissipation methods both give the same results on average. When analysis is completed the drag coefficient should be established well enough to allow good calculations of the wind stress over most of the ocean almost all of the time. Data allowing dissipation estimates of momentum and sensible heat fluxes are now being collected on the CCGS Quadra, one of the ocean weather station PAPA ships, with some measurements in winds of about 25 ms^{-1} already obtained.

Following the investigation of the use of climatological and synoptic type data to calculate fluxes reported in Fissel, Pond and Miyake (1977) for which station P data were used, further work using data from 10 Atlantic weather ships and station N in the Pacific is in progress to see how the results based on the P data may be generalized.

Title: Mixed Layer and Seasonal Thermocline Studies, Participation in JASIN-77 and preparation for participation in JASIN-78.

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Long Range Objectives: Use an array of anchored buoys to add to our knowledge of the time and space variability of surface meteorological and oceanographic parameters over periods of minutes to weeks and a few kilometers to a few tens of kilometers with particular emphasis on the effects of near surface organized convection in the atmosphere.

FY77: OSU participated in the British JASIN-77 air-sea interaction experiment northwest of Ireland during September 1977. Four meteorological oceanographic buoys were anchored for three weeks in a square array about 150 km on a side. The data have been translated, debugged and plotted as time series. The data processor has started computing spectra, variances, cross correlations, coherences and phase lags. Time series were used to help select the study area for JASIN-78.

Results to date indicate that the magnitude of the variance in the water temperature in the near surface thermocline, as a function of time, is highly correlated with the time of day for most of the record. At a depth of 10 m it peaks at mid day and is essentially zero at midnight. Internal waves of the M_2 tidal frequency dominated the internal wave spectra. The semidiurnal variations in the depth of the top of the seasonal thermocline were as great as 67 m.

JASIN-78: Our objectives are to anchor three OSU buoys along with one WHOI buoy in a 2 x 4 km array and a fourth OSU buoy 20 km from the center of the small array. The array will be anchored in Rockall Channel at 59°N Lat. and 12.5°W Long. for two months during the summer of 1978. We plan to obtain a continuous record of water temperature from the surface down well into the seasonal thermocline and of a record of near surface meteorological driving forces. These data will be used: to study the frequency, intensity and velocity of frontal type structures in the mixed layer; to study the variability and organization in near surface meteorological forcing functions and furnish these data to the large number of other researchers who will be studying the mixed layer and thermocline in the area with fixed and towed sensors; to make continuous comparisons between wind data from Aanderaa propeller type anemometers and two different types (WHOI and SIO) of vector averaging wind recorders; to continuously monitor the depth of the mixed layer; and to endeavor to determine horizontal coherence and phase shift as a function of lateral separation as well as phase velocity of the longer period internal waves.

Current Status: Preparation of equipment is well on schedule.

AIR-SEA INTERACTION PROCESSES

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Goals: The goals of this work is to explain relationships between atmospheric forcing and changes in the structure of the upper ocean. In particular we are looking at the manifestations of such interaction at the interface, which can be observed from aircraft or satellites.

Present Work:

A. Analysis of MsMast Data: Data obtained at our Lake Washington facility during 1977 is being analyzed with the following particular topics in mind:

1. Delta T versus u_*: This project concerns evaluation of the temperature deviation of the surface water from lower strata (Delta T) when wind stress (u_*) is acting. We obtained a nice data set for this purpose during November 1977, when the air-water temperature difference was $-10^{\circ}C$.

2. Turbulence over surface waves: This analysis is being done in conjunction with Dr. Søren Larsen of Risø, Denmark, who obtained high frequency turbulence measurements immediately over the waves, while we were recording wave information and other data in August 1977.

3. Eddy diffusivity in waves: A method was found for estimating turbulent diffusivity under waves. This was first explored with a NATO-sponsored student in our summer course in 1976. This will be extended in summer 1977.

4. The high frequency wave gauge: We are also this winter giving close scrutiny to the calibration procedures and the performance of resistance wires at high wave frequencies. This part of the spectrum is of great interest because it is these shorter waves which scatter electromagnetic energy of microwave frequencies. Our data indicate a very different behavior of the spectrum with increasing wind stress in the capillary range compared to the gravity wave range.

B. The JASIN Experiment: We are at present preparing for the JASIN experiment in the North Atlantic July 20 - September 10, 1978, when we will collect data on sea surface temperature and the short and longwave radiative fluxes from one ship and from the NCAR Electra aircraft.

Future Work:

A. Field Experiments:

1. Stress at high winds: The major effort in 1979-80 would be to prepare for and carry out an experiment to obtain direct measurements of wind stress at wind speeds > 15 m/sec. This would take place at an oil rig in the North Sea, December 1979 - February 1980. Dr. Stuart Smith of Bedford Institute of Oceanography will cooperate in this effort. This experiment will be important in itself, if we can extend the range of known values for the "drag coefficient", C_D. The project could also make a valuable contribution to the "verification" effort for Seasat-A's wind stress sensing systems.

2. Participation in MARSEN I: Thought is just being given to possible participation in MARSEN I. (This is a NATO sponsored experiment on Marine Remote Sensing planned for the North Sea, September - October 1979.) We would analyze radiative sea surface temperatures obtained from aircraft. It would be a cooperative effort, where we would be able to extend what has been learnt in the JASIN experiment to a different place, time of year and conditions.

MIXED-LAYER MICROSTRUCTURE

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LONG RANGE OBJECTIVE

To develop an understanding of the physical processes by which heat and mass are transferred vertically in natural waters.

PROJECT OBJECTIVE

The extension of our knowledge of vertical transport processes affecting the surface mixed layer, through observations of temperature and salinity "microstructure".

CURRENT STATUS

In August-September 1977 a month-long cruise as part of the MILE project resulted in 311 microstructure profiles at station P. A preliminary data report "Temperature Microstructure Profiles at Ocean Station P: Preliminary Results from the MILE experiment" (OSU Reference 77-22) has been sent to the ONR distribution list. The process of interpreting this data, particularly in terms of its relation to data from moored and towed instruments, is now under way.

MAJOR ACCOMPLISHMENTS

Microstructure measurements of a temporal sampling density far greater than that achieved before, under adverse weather conditions (40 kt winds).

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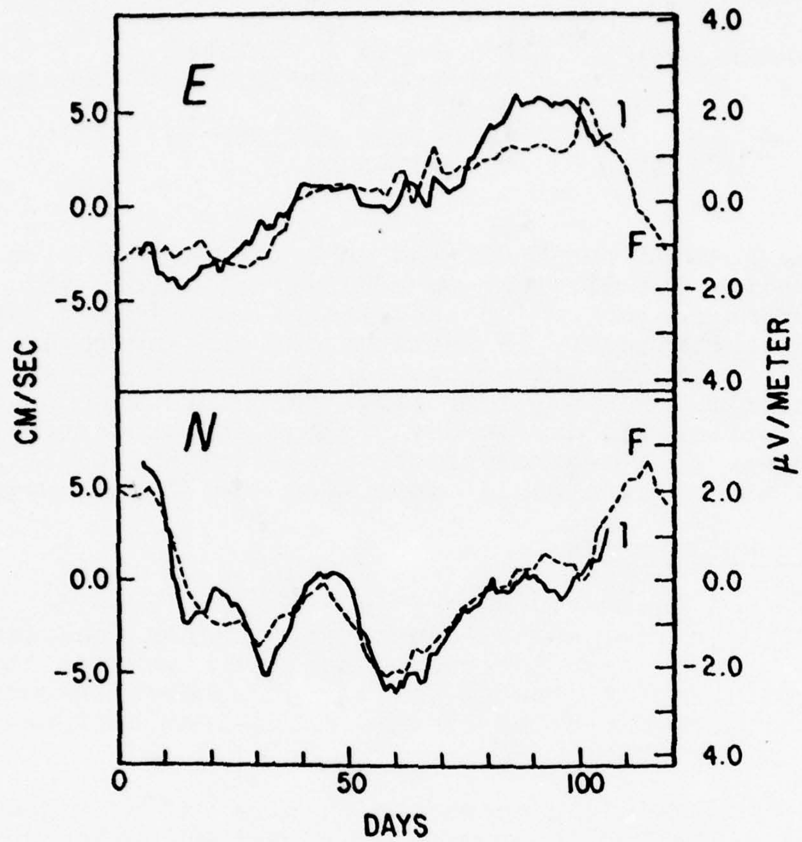
Long Range Objectives. My primary objective is to identify, locate, and measure the small scale processes which bring about the transfer of heat, momentum, and material substances in the oceans. Such knowledge is necessary to understand dissipative processes, the structure of the ocean, and rates of change of oceanic properties. A second objective is to understand electrodynamic processes in the ocean.

Objectives of current work. Primary emphasis in 1976-78 has been on qualitative description of the intrusive tongues which bring together overlapping layers of contrasting water types, and to study the evolution and transport of internal wave energy. Electrodynamic affects of barotropic ocean currents and ocean surface waves have beeen measured.

Current status. Discrimination between internal waves and intrusive tongues can be made on the basis of the spatial and temporal variability of the structure of temperature, salinity, and density. Studies of CTD traces have demonstrated this discrimination and enable evaluation of changes of internal wave energy density with time. The transport of internal wave energy is found to be diffusive on large scales because the wave-wave interaction limits wave propagation to short distances.

Major accomplishments. The diffusion coefficient for internal wave energy has been estimated. A nonlinear effect of short ocean surface waves has been detected on the deep sea floor by electrical measurements. The electrical signature of MODE scale barotropic flows has been found.



Comparison of velocity derived from neutral buoyant floats in MODE with the electric field measured at the sea floor at Station 1. The float data F, analyzed by Freeland and Gould, provide the velocity at Station 1 at a depth of 800 m. The electric field measures the weighted mean velocity from surface to bottom with weight factor equal to the electrical conductivity of the water. The horizontal electric field E is interpreted as horizontal velocity U according to E = - U x B where B is the vertical geomagnetic induction, and indicated by solid line, 1. The upper and lower panels show the east and north components of U respectively. They have been no adjustments. The similarity of the two curves indicates that the electric field is a useful measure of MODE scale barotropic flow which can be made by self-contained apparatus in an Eulerian frame of reference.

Title: NORPAX Program Administration

Investigator: Dr. David L. Cutchin
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The goal of the NORPAX administration office is to provide overall program administration for the NORPAX project which encompasses more than 35 scientists at approximately 19 institutions and government agencies. This administrative function involves proposal coordination and review, long range planning, funding agency interface and day-to-day program administration. It serves as a central point of contact and public relations to the outside world concerning the NORPAX program.

Accomplishments:

1. A Quarterly Report is issued to provide participating scientists, funding agencies and other interested parties a vehicle for keeping abreast of current accomplishments and direction of this multi-institutional program.

2. A mainland coordination base was provided for the NORPAX equatorial experiment which took place during the winter of 77-78.

3. Organized and conducted meeting of NORPAX Co-Principal Investigators and guests. This meeting was the best attended of all Co-Principal Investigator meetings to date.

Upper Ocean Dynamics

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The objective of this study is integration of observational and theoretical ideas to provide methods for predicting changes in the upper ocean on time scales of days to months and for predicting the behavior of statistical descriptions of higher frequency processes.

An experimental study of upper ocean currents and their relation to wind was begun with the NORPAX POLE experiment (J. Phys. Oceanogr., March 1978). Dissatisfaction with instrumentation then available led to an extensive development program leading to a vector averaging current meter based on velocity component sensing propellers (a description appears in the NATO text "Instruments and Methods in Air-Sea Interaction" co-edited by Davis). The current meter appears, from laboratory studies, to be relatively insensitive to the rectification errors associated with rotor/vane meters.

During the MILE experiment eight proto-type current meters were deployed of which one failed. The records show a mixed layer dominated by inertial currents nearly, but not exactly, similar at all depths and in both layers a very energetic internal tide. Integration with dynamical concepts is underway and additional deployments will be made during POLYMODE and JASIN.

Adaptation of acoustic ship's log to use in measuring currents in the upper ocean is underway. Initial improvements in the system have led to achieving useful velocity estimates to depths of nearly 100 m with a depth resolution on the order of 15 m. Methods for routine data logging and archiving are under development.

Upper Ocean variability on the scales of months and hundreds of kilometers has been examined as part of NORPAX. Using statistical models the relation of North Pacific sea surface temperature to the overlying atmosphere as described by surface pressure, has been examined (J. Phys. Oceanogr., May 1976 and April 1978). The dominant connection appears to be atmosphere driving ocean with about a one month lag. In certain seasons, however, the ocean state can be used to predict subsequent atmospheric states, suggesting a possible feedback. The nature of the atmospheric forcing of the ocean is under further study using sea level along the west coast of North America and steric adjustment off California.

Recently completed was an observational study of wind generated surface waves by Davis and Lloyd Regier, now of M.I.T. Methods of estimating directional spectra were developed and applied to data from BOMEX. This showed universal spectra to be only a first approximation spectra of the frequency to the minus fifth power type to be unusual, the spectrum to be universally more directionally of nonlinear control of the spectrum.

Investigation of Internal Wave

Dissipation and Small Scale Temperature

Structure in the Ocean

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This investigator's general interests are presently the theoretical modeling of oceanic processes. His goal is to derive models that describe the basic physics and can account for the available data. In the particular context of internal waves a basic problem is to estimate what part they play in the overall energetics of the oceans. The overall, long-range purpose of the investigation outlined in this proposal is to determine what is (are) the physical mechanism(s) by which internal waves are dissipated, at what scales these processes occur, and what the signature of those events might be.

The specific objective of the project is to investigate the physical processes that determine the small-scale temperature fluctuations in the ocean (scales from 100 to 0.1 m in the vertical). We shall examine what are the respective contributions from internal waves and fine structure to the observed variability, and how the transition from one regime to the other occurs as the wave number increases.

We shall attempt to determine at what scales internal waves are dissipated by breaking and what the signature (i.e. the resulting fine structure) of those events might be: To this end we shall derive a statistical description of the observed temperature structure, which would be helpful in interpreting the data. We would also like to define the optimum set of measurements required to observe, separate, and quantify the internal wave contribution to the small-scale temperature fluctuations.

Thus our objectives involve the simultaneous investigation of the physical processes, their modeling and description, and the theoretical problems posed by their measurement.

This is a new project started in February 1978.

DYNAMICS OF THE OCEAN SURFACE MIXED LAYER

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LONG-RANGE OBJECTIVES

To understand the dynamics of exchange of heat and momentum at the ocean-atmosphere interface and its relation to the deeper ocean.

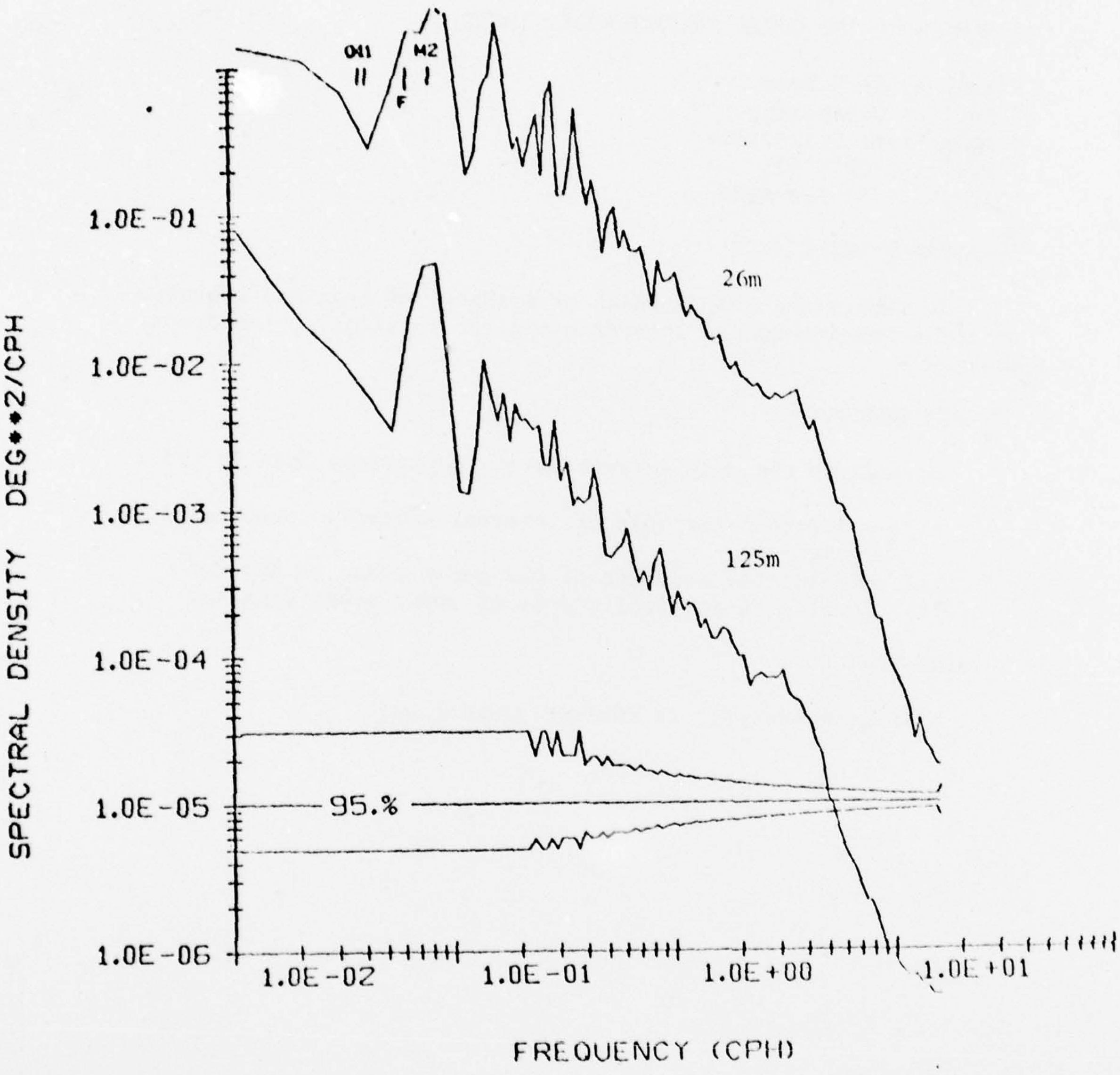
PROJECT OBJECTIVES

To analyze the MILE current meter-temperature data in order to:

(i) understand the role of internal waves in upper ocean dynamics;
(ii) examine the response of the upper ocean to storms;
(iii) develop theoretical models of upper ocean dynamics

CURRENT STATUS

MILE data analysis is currently under way.



Temperature spectra at MILE-PAPA for 26m and 125m. Note strong M2 tidal signal, weak inertial peak (labelled F), $(\text{frequency})^{-2}$ dependence from 0.1 to 1.0 cph, strong cut-off at 3 cph. These features are common in all temperature records from MILE despite variation in levels of the spectra with depth.

Transient Processes in Ocean Currents

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Long range objectives:

Develop a better understanding of the kinematics, dynamics and transient behavior of well-defined, intensive ocean currents and, furthermore, of the role of intensive ocean currents in air sea feedback systems and in oceanic heat budgets.

Project objectives:

Equatorial Currents (GATE): Study of time-dependent, three-dimensional structure of the currents in the immediate vicinity of the equator, with emphasis on the Equatorial Undercurrent and its long-period fluctuations.

Somali Current (INDEX): Obtain several year-long time series of currents and sea surface temperature (by remote sensing methods) to determine oceanic response in a western boundary current subject to large-scale seasonal wind reversals. An intensive field study in 1979 is scheduled to complement these several year long observations by focusing on the Somali Current and the adjacent equatorial region.

Current Status and Major Accomplishments:

Observations from the GATE Equatorial Oceanographic Experiment reveal large-scale meandering of the westward-flowing South Equatorial Current and of the eastward-flowing Equatorial Undercurrent with time scales of 2 to 3 weeks. These observations interpreted as atmospherically forced waves as well as large-scale barotropic instabilities, were found to dominate the fluctuations in the equatorial Atlantic. The analysis of large volumes of satellite-sensed sea surface temperature data allowed for the first time to reliably pinpoint wavelength and propagation properties of equatorial waves.

Somali Current: Long-term current and temperature records from several locations in the Somali Current north and south of the equator constitute the first modern oceanographic time series made in this region. These records and simultaneous observations by satellite borne temperature sensors, begin to reveal the outline of a charateristic annual cycle of the Somali Current. Two major features of this cycle are the omnipresence of very large eddies and a deep counterflow under the Somali Current. The southwestward directed mean flow (see Table 1) is observed throughout the year at relatively shallow depths. These measurements in conjunction with records off Kenya in 1976 imply that the Somali Current may be limited to a very thin top layer and thus differs substantially from other boundary currents such as the Gulf Stream and Kuroshio.

Table 1. Mean speed and direction of currents recorded 39 km off the Somali Coast near latitude $4^{o}33'$N during the two monsoon seasons in 1977/78.

Time period of observation	Sensor depths (m)	Speed (cm/sec)	Flow towards (^{o})
During Southwest Monsoon:			
1 June 77 - 3 Nov 77	210	19	213
During Northeast Monsoon:			
3 Nov 77 - 11 Feb 78	210	41	206
During Southwest Monsoon:			
1 June 77 - 3 Nov 77	590	15	209
During Northeast Monsoon:			
3 Nov 77 - 11 Feb 78	590	19	204

Regional Studies in Physical Oceanography

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Scientific Goals

Our long-range objective is to contribute to the understanding of the dynamics of ocean circulation. At this point in time, our interest is focused on the mesoscale circulation features of the Gulf of Mexico and the Caribbean Sea. Due to the rich variety of dynamic phenomena found in the circulation of these basins, we believe that studies of their circulation will be rewarding by not only adding to the description of the basins' regional oceanography, but by also supplying information on the generation and interaction of dynamic processes common to all ocean basins.

Objectives

To calculate by 1° squares the long-term mean seasonal wind stress and wind stress curl for the Caribbean Sea, to determine if the annual variation in the magnitude and distribution of these parameters can provide a dynamical explanation for the observed temporal variability of the Loop Current system in the eastern Gulf of Mexico.

Current Status

The historical surface marine observations from the National Climatic Center TDF-11 deck have been sorted by 1° squares; edited, to eliminate incomplete or unrealistic records; and utilized to calculate surface wind stress (using the bulk aerodynamic method) and wind stress curl. The results of these calculations are now being put into analyzable form.

OCEANIC THERMAL RESPONSE TO ATMOSPHERIC FORCING

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(408)646-2373/2552

The objective of this research is to isolate and document those changes in near-surface oceanic thermal structure parameters that are related to atmospheric forcing. Our particular interest is in the understanding and simulation of changes on diurnal, atmospheric cyclone and monthly time scales. A combined modeling and data analysis approach is used to obtain a more complete view of the time evolution in the absence of complete oceanic data, and to extend our understanding of the dominant physical processes.

We have found a characteristic response in terms of mixed layer temperature and depth due to the passage of atmospheric cyclones (Elsberry, Fraim and Trapnell, 1976, J. Geophys. Res.). It was also shown that a major fraction of the atmospheric forcing is concentrated in a relatively small fraction of the time, and that these periods can be associated with synoptic time-scale forcing events (Camp and Elsberry, 1978, J. Phys. Oceanogr.). A long-term statistical study of these forcing events indicated that the accompanying sea surface temperature changes may account for the net cooling for the entire month or season (Elsberry and Camp, 1978, J. Phys. Oceanogr.). Application of a new one-dimensional bulk model (Garwood, 1977, J. Phys. Oceanogr.) has demonstrated the variability of the turbulent mixing on diurnal and storm periods. The coupling of the diurnal and atmospheric cyclone forcing during the spring appears to be capable of explaining interannual differences in upper ocean thermal structure. Of most importance are cases of rapid transition during one daily heating cycle from a winter regime of deep mixed layers to a summer regime with shallow layer depths, which then establishes the characteristic thermal structure for several months.

Dynamic Topography from Temperature Maps:
A Monitor of Ocean Circulation Changes

William J. Emery, Principal Investigator, (713)-845-2947
Dept. of Oceanography, Texas A&M University
College Station, Texas 77843

Long-range scientific objectives of the Principal Investigator:
Through the study of new and existing data develop an understanding of the distribution of temperature and salinity and their variations. To use this understanding to develop techniques which will allow interpretation of ocean dynamics from expendable bathythermograph (XBT) data. To promote the use of cost effective methods of data collection (XBT's, XSTD's, etc.), to acquire information of the spatial and temporal changes in the circulation of the ocean.

Objectives of the project: To develop techniques which will allow computation of 0/500 db dynamic height in the North Pacific between 30 and 50°N from XBT thermal structure. Using these techniques produce monthly maps of 0/500 db dynamic topography to monitor the changes in the geostrophic circulation.

Current status of research: Computational procedures using mean salinity profiles and mean temperature-salinity curves have been developed to infer salinity for dynamic height calculations. Maps of 0/500 db inferred dynamic topography have been computed from an XBT temperature climatology (provided by White and Bernstein) and compared with existing bi-monthly maps of true dynamic height. Individual monthly maps of inferred dynamic topography have been computed from TRANSPAC XBT maps to provide a 2½ year monthly time series of the geostrophic circulation in the North Pacific.

Major accomplishments: Mean salinity profiles have proved useful in inferring salinity from depth in the region north of 40°N. Here salinities from temperature-salinity curves led to large uncertainties in 0/500 db dynamic height (∿10 dyn cm) while the salinity profiles resulted in uncertainties of about 2-3 dyn cm in regions north of the Subarctic Front (∿40°N). Bimonthly maps of inferred dynamic height computed from an XBT climatology compare well with exisiting maps of true dynamic height. Individual monthly maps reveal significant changes in the circulation of the West Wind Drift in the Eastern North Pacific. A paper reporting these results has been prepared and submitted. Present plans are to use the monthly maps of inferred dynamic topography to compute such quantities as geostrophic heat advection, and variations in the momemtum flux.

XBT Swath Analysis, A Study of Spatial Variability

Co-Principal Investigators:

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Dept. of Oceanography, Texas A&M University,
College Station, Texas 77843

John P. Dugan, (202)-767-3756
Code 8340, Ocean Sciences Div.
Naval Research Lab
Washington, D.C. 20375

Long-range scientific objectives of this investigator*: In addition to those objectives previously stated, this investigator desires to develop a set of statistical techniques to properly evaluate XBT data (sections and swaths) in terms of mesoscale features.

Objectives of this project: To better describe the mesoscale variations in temperature, density and sound velocity in the upper ocean. To use available swath XBT data to produce a three dimensional, surface to the bottom picture of sound velocity structure for use by the acoustic community. To evaluate statistical procedures for a meaningful description of mesoscale features.

Current status: Working with a swath in the North Pacific historical temperature and salinity data have been used to extrapolate the XBT data and to compute sound velocity. A paper describing this procedure and the resultant sound velocity structure has been submitted. We are now working to statistically analyze the mesoscale features observed in the XBT data.

Major Accomplishments: Surface to 3000m sections of sound velocity show important variations in sound velocity structure especially within the sound channel. The effects of these variations on propagation are being evaluated. The extrapolation technique for temperature is least successful in extending 500m temperature profiles down to 800m. Therefore, future swaths should use all 800m XBT probes.

Potential density, energy and vorticity computations

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Density of seawater varies with salinity as well as temperature and pressure making explicit calculation of an adiabatically leveled reference density field impossible. The topography of the observed density field in terms of the leveled potential density field is necessary for computing available potential energy, potential vorticity and for mapping tracer and indicator variables on material surfaces of constant potential density. An accurate numerical procedure has been developed to compute the reference field from CTD profiling stations. The procedure has been applied to MODE-1 density stations to estimate available potential energy and is being used to examine the potential vorticity conservation equations for the MODE-1 density and velocity measurements. The techniques developed will be used on other data sets as they become available.

Moored Array Program

N. P. Fofonoff, W. J. Schmitz, Jr., and J. R. Luyten

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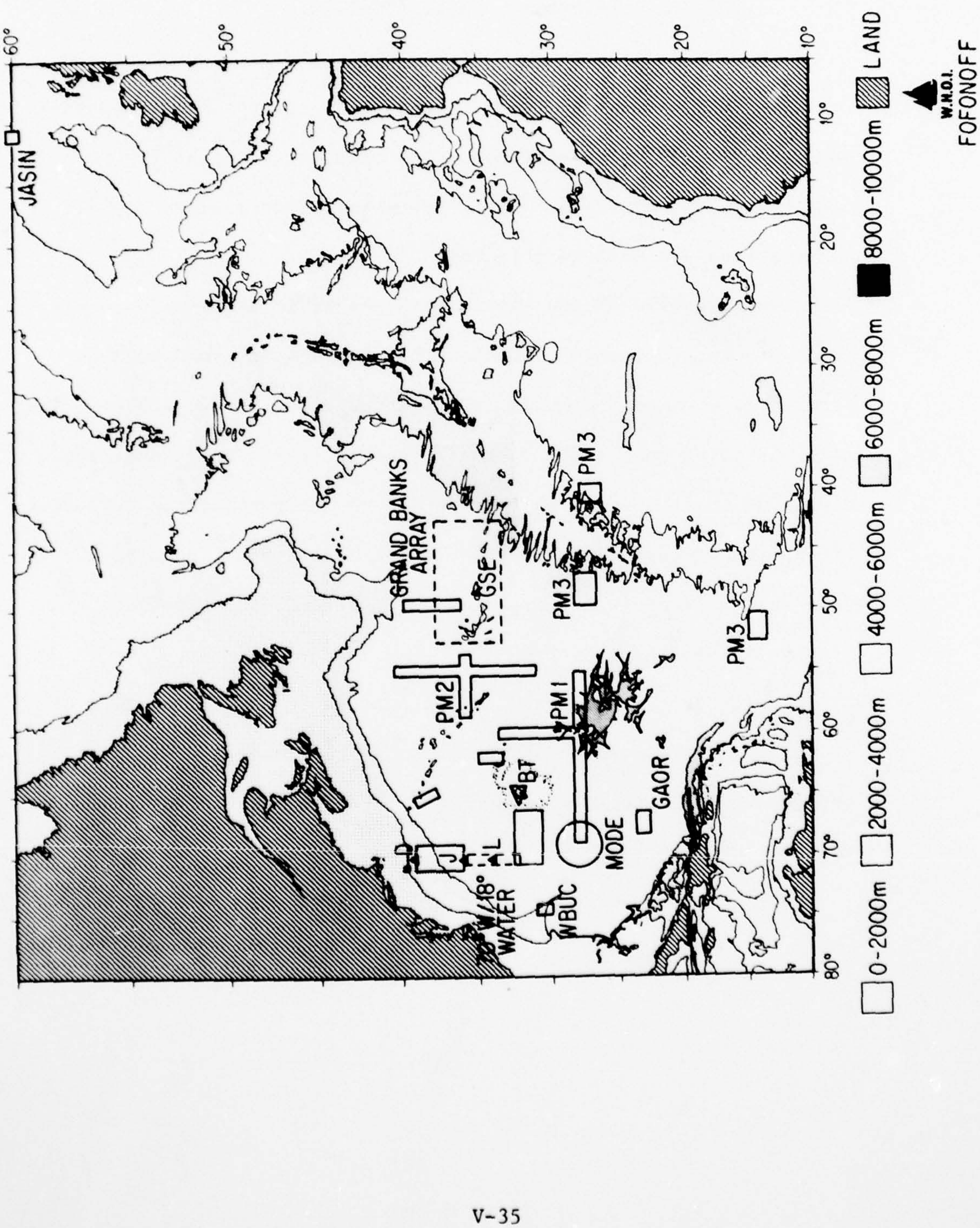
Woods Hole MA 02543

(617) 548-1400 Ext. 525 (NPF), Ext. 541 (WJS), Ext. 541 (JRL)

The broad objectives of the moored array program are to explore and describe the velocity and associated temperature, salinity and density fields in the oceans over a broad range of time and space scales; to interpret the data in terms of theoretical and conceptual models; and to improve and develop instruments and platforms needed to obtain the data desired.

Research is carried out jointly with investigators from within the moored array program and with scientists associated with other programs, departments and institutions. Each scientist utilizing moored array program resources will describe his personal research elsewhere in this report. The principal investigators listed above are responsible for the technical quality of the observations made, and for encouraging the best possible cooperative experiments. With respect to technical quality: (a) mooring recovery is nearly 100%, (b) current meter data return is near 90%, (c) all commitments made in the last few years have been successfully completed, including innovative efforts such as a tri-mooring, the first large-scale sediment trap moorings, and one-year deployments. It is felt that the results of experiments utilizing our capability are playing a fundamental role in forming the observational base for contemporary oceanography.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"Theoretical Study of Oceanic Frontal Dynamics and Thermodynamics"

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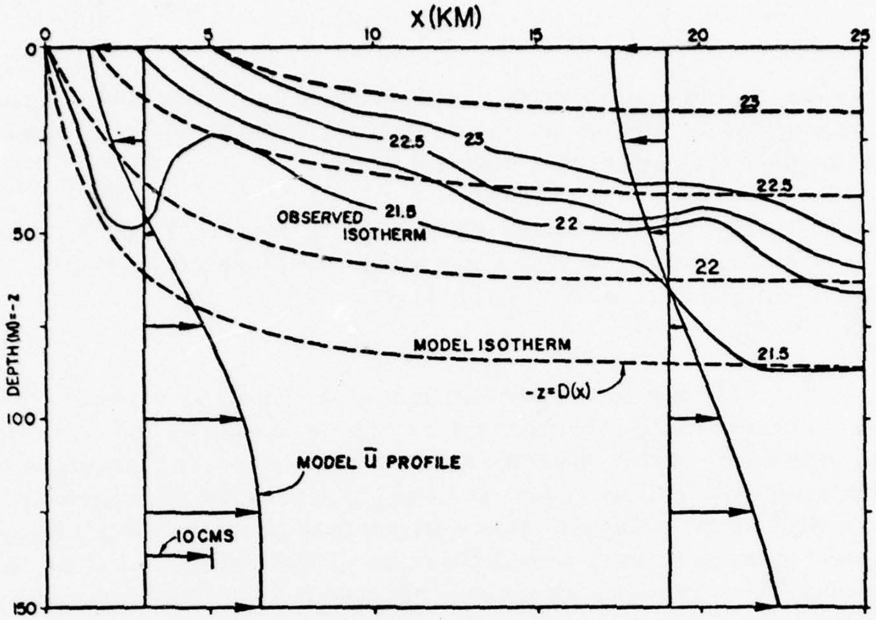
College of Marine Studies
University of Delaware, Newark, DE 19711
Telephone (302) 738-1212.

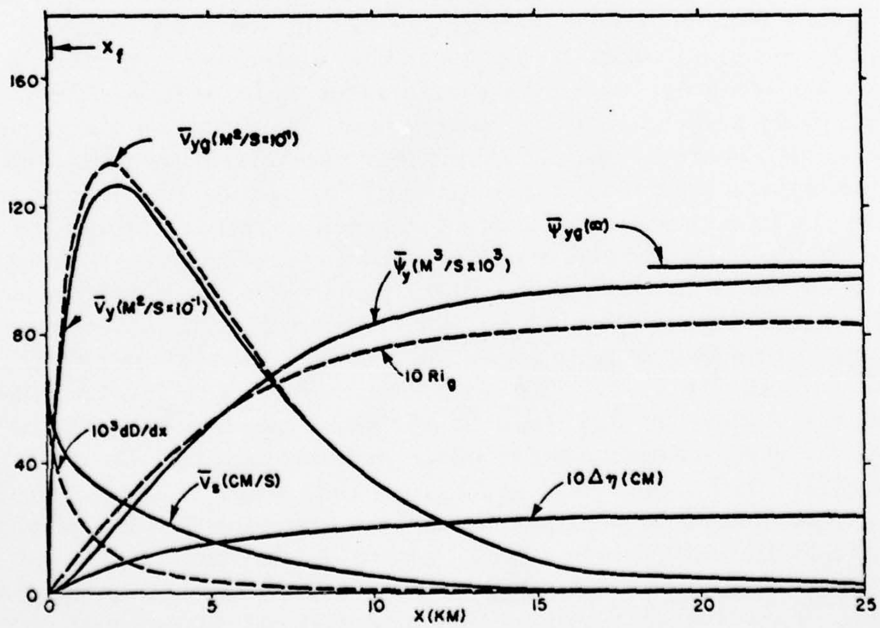
The long range scientific objective of the principal investigator is to develop understanding and predictive capability for oceanic frontal dynamics. Both theoretical modeling and field observations are used to this end.

The objective of the current project is to develop an integral model of oceanic frontal dynamics that includes thermodynamics, permitting the model circulation to accomplish its own mixing. The model is to be applied to a broad range of fronts from small-scale estuarine fronts, where earth rotation is unimportant and turbulent transport processes dominant, to large scale fronts, such as the Gulf Stream front, where rotation is important, but turbulent transport less so.

In its current status, the project has led to formulation of the proper integrated equations for mass continuity, downstream and cross-stream momentum and advection-diffusion of buoyancy, together with appropriate boundary conditions.



Model isotherms (dashed lines) for the Sargasso Sea front compared to the observed isotherms of Voorhis (1969) (solid lines). Also shown are two model cross-stream $\bar{u}$ velocity profiles.



Downstream flow variables from the model for the Sargasso Sea front, including surface velocity $\bar{v}_s$, volume flux per unit width $\bar{V}_y$ and the geostrophic value, $\bar{V}_{yg}$ and the total volume transport $\bar{\psi}_y$. Also shown are sea surface elevation anomaly $\Delta\eta$, Richardson number Ri_g and interfacial slope dD/dx.

"Measurements of velocity, temperature and conductivity fluctuations during the mixed layer experiment (MILE) by a towed ocean profiling system - data analysis"

Carl H. Gibson, Associate Professor of Engineering Physics and Oceanography, Scripps Institution of Oceanography, La Jolla, California 92037 (714) 452-3184

Mixing processes in the ocean such as turbulence are characteristically intermittent in time and patchy in space due to the effects of stable stratification. Estimates of viscous and diffusive dissipation rates (ϵ and χ) from the MILE data indicate that mean values of these important quantities may be determined by a relatively small fraction of the volume of fluid for a given layer. This is so when $(\epsilon, \chi)_P/(\epsilon, \chi)_O$ is greater than V_P/V_O, where the subscripts indicate values in the active patches compared to the less active background, and V is vol. FR since $\overline{(\epsilon, \chi)}_{Layer} = (\epsilon, \chi)_P V_P + (\epsilon, \chi)_O V_O$. Patches of various sizes were observed, and the value of (ϵ, χ) seems to increase with the size of the patch. Consequently the average value $\overline{(\epsilon, \chi)}$ estimated for a given layer will increase until the size of the record averaged is larger than the separation of the largest patches. Patches of active mixing were observed in MILE extending over 50 meters in the horizontal separated by over a kilometer, with dissipation rates at least two orders of magnitude greater than the background. Measurements were made with heated and cold microbead thermistor velocity and temperature sensors, microconductivity probes (resolution less than 1 cm) as well as sensors for mean quantities, mounted on the double hulled towed ocean profiling system shown schematically in the figure. Surface ship forces were decoupled by a tether pulley arrangement so that vertical displacements were reduced to a few centimeters, the linear acceleration spectra to 10^{-3} to 10^{-4} (m/s^2) /hz in the bandwidth 1 to 100 hz with roll rates of order 0.1°/sec at surface wave frequencies, so that the body induced sensor noise was minimized. Over 35 hours of $(C, C', T, T', u, u', a_1, a_2, a_3, p)$ data were collected during ten days of tows at depths from 0-60m covering 300 km of water in the MILE experiment array, where C is conductivity, T is temperature, u is velocity, a is acceleration and p is pressure. Data analysis will include a statistical description of the intermittency of mixing parameters and an attempt to categorize the hydrophysical states of the fluid; layered, inactive, active and fossil turbulence for example.

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PHYSICAL OCEANOGRAPHY PROGRAM.(U)

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Ocean Modelling Newsletter
Principal investigators: Drs. A. E. Gill, D. L. T. Anderson and P. D. Killworth, D.A.M.T.P., Silver Street, Cambridge, U.K.

This project was designed to establish an informal newsletter as a means of communication of preliminary research results among United States and European scientists on all phases of ocean modelling. Now that the teething troubles are over, articles are arriving at a steady rate and 12 newsletters have now been circulated, with articules by 54 authors from 8 different countries. The newsletter is widely circulated within the Navy and academic community, there being 451 names on the current mailing list.

a. Sea Level and Sea Surface Temperature Expressions of Ocean Transients as Viewed From Satellite.
Arnold L. Gordon
Lamont-Doherty Geological Observatory, and Department of Geological Sciences of Columbia University, Palisades, New York 10964
914 359 2900 Ext 325

b. General scientific objectives of A.L. Gordon is the study of transport of ocean characteristics by spreading of water masses on a variety of scales. Cross frontal exchange in regard to oceanic regime to regime transfer of ocean characteristics and generation of water masses is of particular interest.

c. Study of the structure evolution and translation of sea level variations associated with geostrophic turbulence with horizontal scales of 100-1000 km, and their relation to sea surface temperature. The initial objective is to utilize SEASAT-A altimeter and radiometer data in the Western North Atlantic to study transient geostrophic features generated by the Gulf Stream system (meanders, rings and eddies).

d. The project will begin in May 1978 with a study of the GEOS-3 altimeter and other satellite radiometer data in the Northwest Atlantic for the period February-March 1976, when particularly intense Gulf Stream rings were present. When SEASAT-A data becomes available in October or November 1978, we will shift to these records.

e. No accomplishments, since project is a new start.

Project title

XBT Sections in the Northeast and South Atlantic.

Principle Investigator

W. J. Gould,
Institute of Oceanographic Sciences,
Wormley, Godalming,
Surrey GU8 5UB, U.K.

Long range scientific objectives of PI

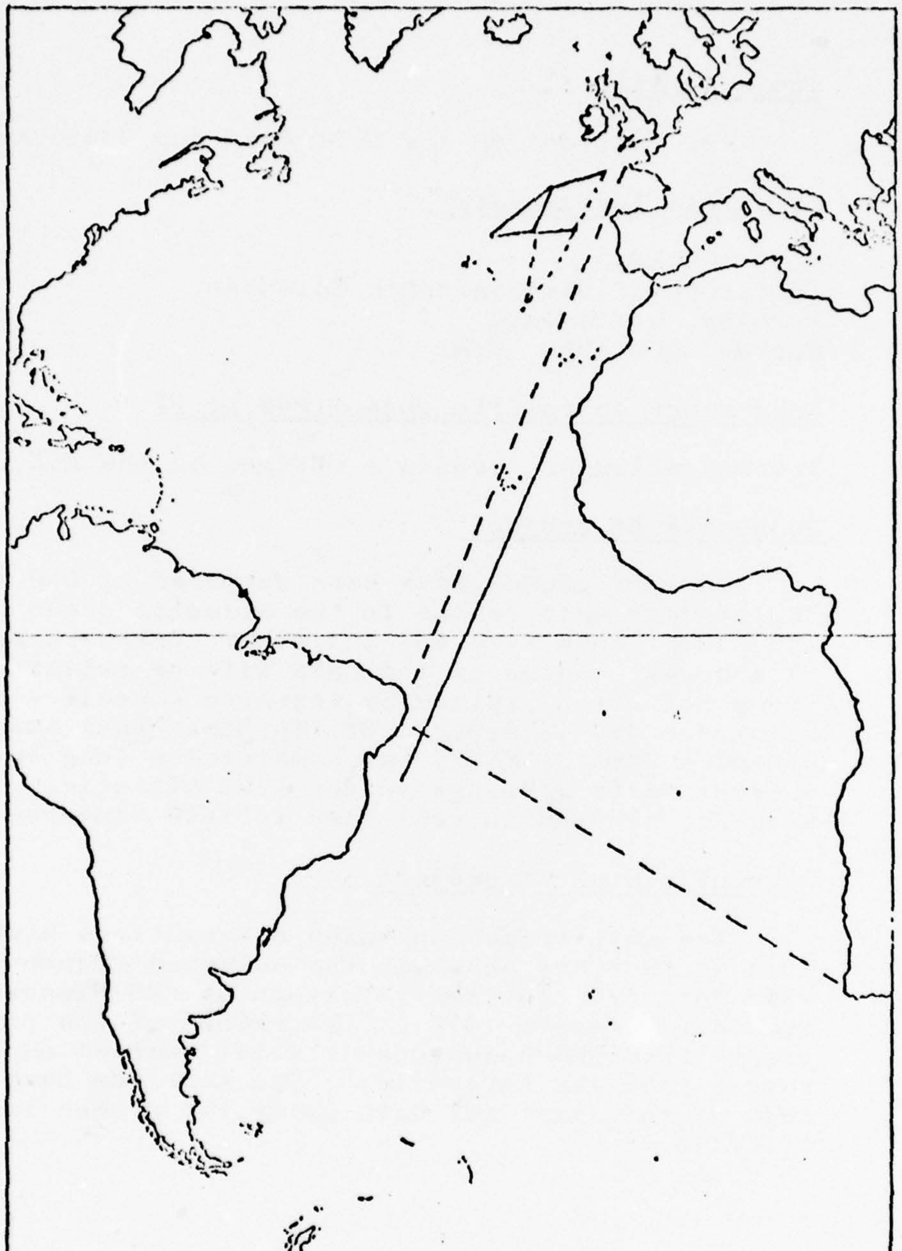
Investigation of mesoscale motions in the N.E. Atlantic.

Objective of project

T-7 XBT probes have been supplied by ONR to be deployed on ship tracks in the Atlantic ocean during 1977/78. Ship time and all other costs are borne by UK sources. Some of the data will be collected from areas not often visited by research vessels - the remainder are in support of the North East Atlantic Dynamics Study (NEADS) which maintains long term current meter moorings in the N.E. Atlantic. The data are relayed in real time fo FNWC Monterey.

Current status of project

The ship tracks on which observations have or will be made are shown in the attached figure together with data from the section taken by RRS Discovery in November/December 1977. The return of the original traces from HMS Endurance is still awaited on her return from the Antarctic. The sections have yielded some of the first XBT data using T-7 probes in the N-E Atlantic.



XBT lines already completed (solid lines) and planned (dashed lines).

SMALL SCALE MIXING PROCESSES

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Applied Physics Laboratory
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Seattle, Washington 98105
206-543-1353

Long-Range Scientific Objectives of the Principal Investigator

My long-range scientific objectives are to develop a quantitative understanding of the dissipative processes in the ocean and their role in the large-scale, time-averaged budgets of heat, salt, and momentum. To achieve this understanding it is necessary to observe microscale fluctuations of temperature, salinity, and velocity to scales less than a centimeter and to relate the dissipative structures found to the fine-scale variability occurring over scales of from a meter to about 10 kilometers. Since these same variables also determine the velocity of sound, some of the processes and structures observed are major factors causing acoustic fluctuations in frequency bands of practical importance to the Navy.

Objectives of the Project. There are two phases of the project. One is to assess the levels of small scale, i.e. centimeter, mixing in the upper ocean and the other is to study the evolution of intrusive water bodies. The intrusions have vertical scales of from 1 m to tens of meters and horizontal scales up to tens of kilometers. They appear to be major factors in the heat and salt fluxes of the ocean and in short range sound speed anomalies.

Status. Free-fall observations of small scale mixing and towed measurements of the larger scale density field were made under heavy weather at Ocean Station P during MILE in August 1977. The observations were successful and are currently being analyzed. Measurements of the effect of meso-scale eddies on the mixing will be made during Polymode during June 1977.

Major Accomplishments

Previous observations have shown that the level of small scale mixing in the main thermocline of the Pacific is much lower than can be consistent with oceanic models that rely upon significant vertical turbulent diffusion. The levels do show significant variation from one month to another, due either to the passage of meso-scale eddies or to variations in the energy input to the internal wavefield. By contrast the Equatorial Undercurrent has two regions of intense vertical turbulence. The Gulf Stream, however, does not.

The dynamics of the near surface layer were shown to be strongly affected by lateral advective processes rather than wholly governed by vertical mixing.

A. PROJECT TITLE: Mesoscale ocean-atmosphere response studies during the 1978 Joint Air-Sea Interaction (JASIN) Experiment

PRINCIPAL INVESTIGATOR: David Halpern

ADDRESS: Pacific Marine Environmental Laboratory
3711-15th Avenue N.E.
Seattle, Washington 98105
(206) 543-5284

B. LONG-RANGE SCIENTIFIC OBJECTIVES: Parameterization of wind-generated physical processes occurring in the upper ocean.

C. PROJECT OBJECTIVES: (1) Description of the spatial variations of the near-surface wind-stress and upper ocean currents for distances between 10 km and 100 km. (2) Intercomparison of Savonius rotor, acoustic, electromagnetic and propeller-current meters. (3) Intercomparison of propeller and 3-cup wind recorders.

D. CURRENT STATUS: Moorings and equipment are being prepared for deployment in July from the R.R.S. *Shackleton*.

A. PROJECT TITLE: Variability of wind-generated upper ocean currents during the Mixed Layer Experiment (MILE)

PRINCIPAL INVESTIGATOR: David Halpern

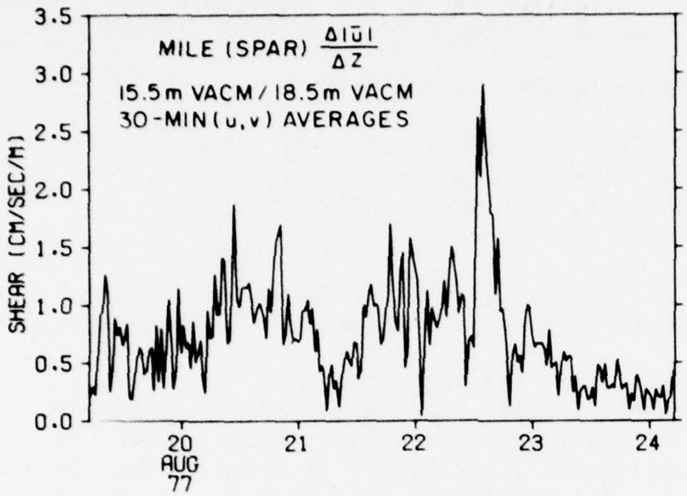
ADDRESS: Pacific Marine Environmental Laboratory
3711-15th Avenue N.E.
Seattle, Washington 98105
(206) 543-5284

B. LONG-RANGE SCIENTIFIC OBJECTIVE: Parameterization of wind-generated physical processes occurring in the upper ocean.

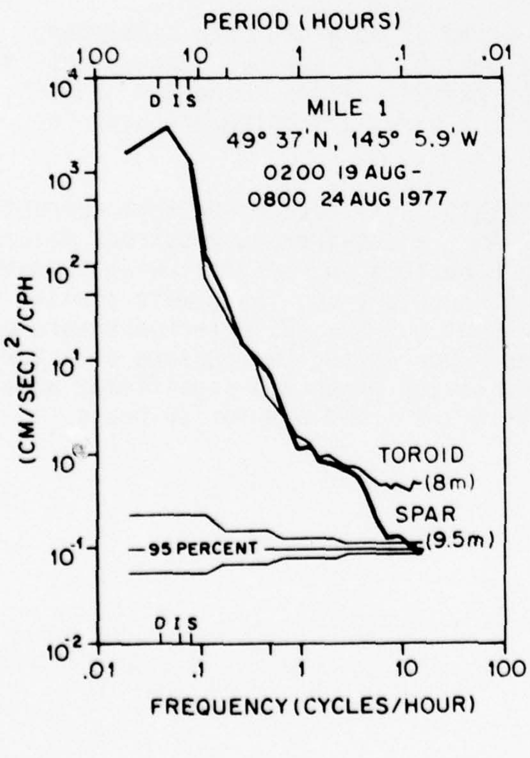
C. PROJECT OBJECTIVES: (1) Description of the vertical profile of low-frequency (cutoff frequency $\sim$ 2 cph) components of the horizontal velocity and temperature fields within the upper ocean, including the mixed layer. A shear in the mixed layer of 0.01 sec^{-1} will contribute significantly to the turbulent energy budget and cannot be ignored in models of mixed layer dynamics. (2) Description of the reliability of near-surface moored current measurements. (3) Relationship between wind-forcing and vertical finestructure of dynamic stability as represented by the Richardson number. (4) Description of the time variations of wind-generated internal wave energy.

D. CURRENT STATUS: Processing of data has been completed. Results of intercomparison of near-surface measurements made from different types of current meters suspended beneath different kinds of surface buoys are being prepared for publication.

E. SIGNIFICANT ACCOMPLISHMENTS: (1) Determined that current measurements made with AMF vector-averaging current meters suspended at 8 m depth beneath a surface-following toroidal buoy and at 9.5 m depth beneath a spar buoy were similar at frequencies less than about 5 cph. (2) Observed shears of 0.03 sec^{-1} in the mixed layer during the passage of a low-pressure (992 mb) storm having winds and significant wave heights in excess of 15 m sec^{-1} and 3 m for 36-hours.



Time-series of the current shear computed from 30-min vector-averaged measurements recorded at 1.875-min intervals by AMF VACM's at 15.5 m and 18.5 m depths beneath a spar buoy. An intense summer storm began at ~ 1200 Z 22 August. The thickness of the surface mixed layer increased from 10 m at 0500 Z 22 August to 40 m at 2100 Z 22 August. Maximum wind speed (20 m sec^{-1}), significant wave height (4.8 m) and surface wave amplitude (4.5 m) occurred at about 0000 Z 23 August.



Kinetic energy densities of AMF VACM measurements recorded at 8 m and 9.5 m depths beneath a surface-following toroidal buoy and a spar buoy, respectively. During the observation period a summer storm with maximum wind speed of 20 m sec^{-1} and maximum significant wave height of 4.8 m passed over the experimental site. During a 24-hour interval of the storm when wind speeds were in excess of 15 m sec^{-1}, the r.m.s. deviation between 1.875-min values of the east (or north) component was about 5.0 cm sec^{-1}.

NUMERICAL STUDIES OF THE DYNAMICS OF LARGE SCALE OCEAN ANOMALIES

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The long-range scientific objective of my research is to improve our understanding of the large scale thermal variability in the upper layers of the ocean and to develop a dynamical, numerical model capable of simulating that variability with proven skill. It is expected that this improved understanding and modeling skill will increase the Navy's capability to predict environmental factors which are required to meet various operational needs.

The objective of this project is to continually develop and improve a numerical model of the North Pacific Ocean and to use the model to identify processes responsible for the formation and evolution of large-scale thermal anomalies in the open ocean. This is being done by performing a series of numerical simulations of such anomalies starting from observed initial states in the ocean. An improved version of Haney's (1974, J. Phys. Oceanogr.) ten-level primitive equation model of a closed rectangular basin is being used for the simulations. The observed initial conditions are being obtained from the monitoring program (TRANSPAC) of the NORPAX Anomaly Dynamics Study.

Three numerical experiments have been completed. The first experiment makes use of idealized anomaly patterns in both the atmosphere and the ocean and thereby provided background information for the interpretation of the more complicated experiments using observed data. The two experiments utilizing observed data are for the Fall and Winter of 1971-72 and 1976-77 respectively. Both of these periods were characterized by intense anomalies in the atmosphere. A contrasting case, with weak atmospheric anomalies, is being studied at the present time. The above model simulations and the analysis of new TRANSPAC data both suggest that surface wind mixing may be an important new mechanism for anomaly development. In order to realistically test this mechanism, various aspects of the numerical model are being improved. These include improved representation of the atmospheric wind forcing, introduction of salinity as a prescribed variable, and the introduction of an explicite prognostic formulation of the well mixed surface layer (Garwood, J. Phys. Oceanogr. (1977)).

The major accomplishments during the past two years are (a) the successful simulation of large-scale anomalies starting with observed data from the ocean, and (b) the demonstration, by model simulation, that anomalous atmospheric wind forcing alone (with climatological heating) can account for a considerable fraction of the observed anomaly development at the surface (see the figure on the next page).

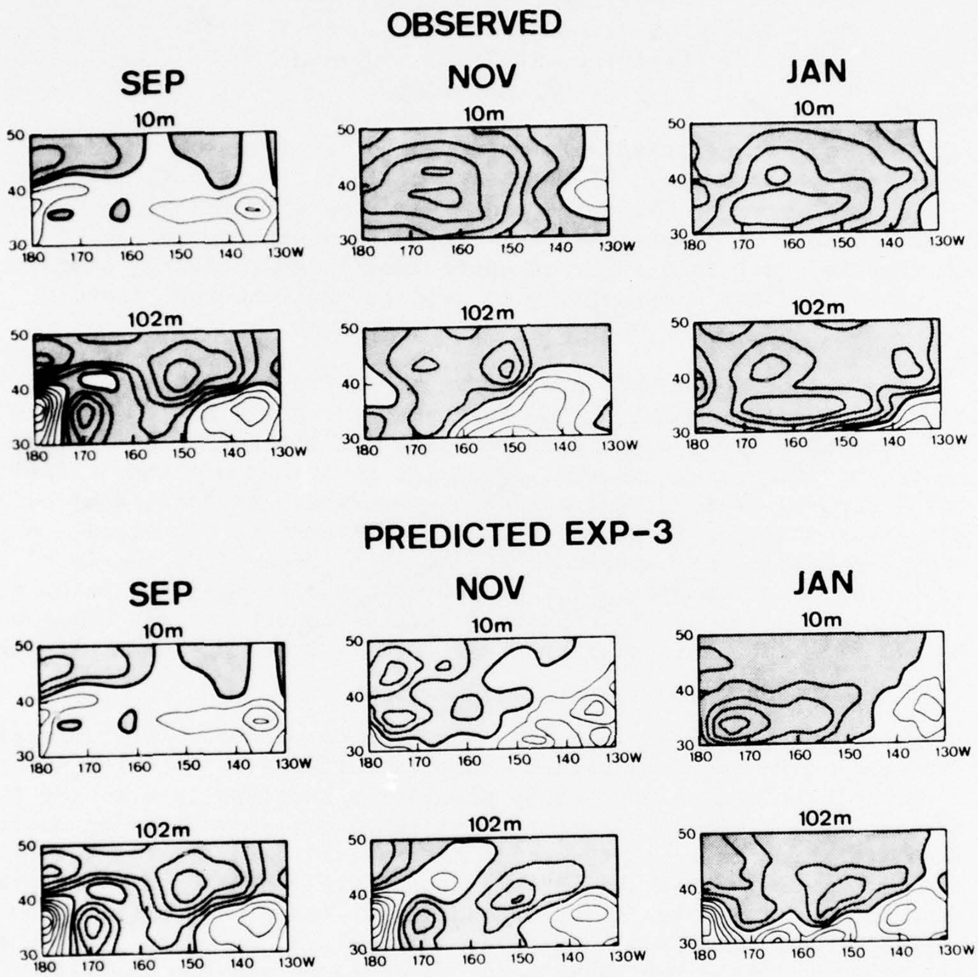

Fig. 1. Top panels show the monthly mean temperature anomalies observed in the North Pacific Ocean during September 1976 (first column), November 1976 (second column) and January 1977 (third column). Lower panels show the corresponding anomalies simulated by the numerical model. The 4-month simulation made use of observed anomalous wind forcing but climatological heating. The contour interval is 0.5 C at 10 m and 0.2 C at 102 m. Negative anomalies are shaded.

1. Equatorial Circulation Study

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Phone: (808) 948-7894

2. Long-range objectives of the principal investigator

To participate in the ongoing effort to determine the dynamics of the equatorial oceans. The FGGE intensive activity in the equatorial region offers the opportunity to measure a given oceanic effect simultaneously with a multitude of other observations. Hopefully this will allow us to correlate phenomena in both space and time and to identify the causal dynamic relationships between these phenomena.

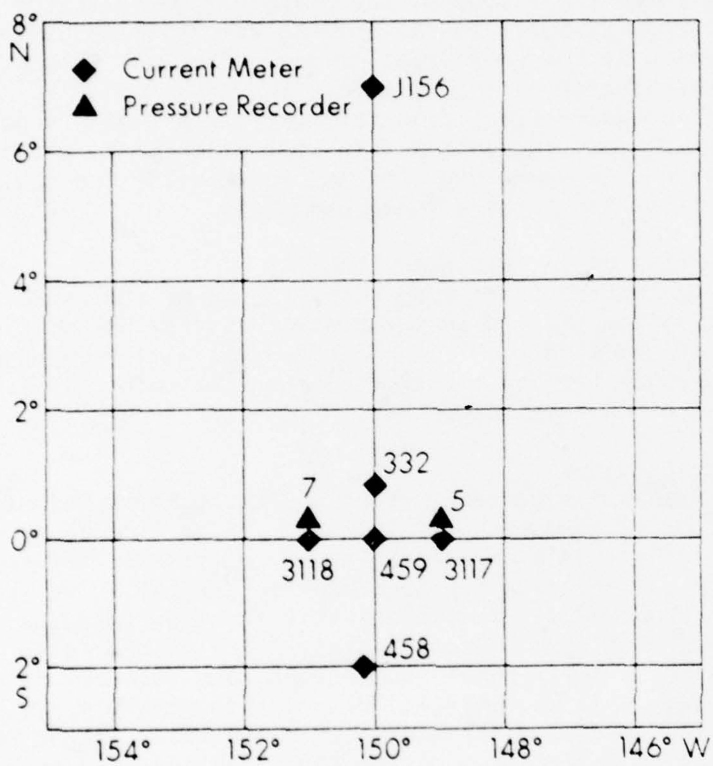
3. Objective of the project

To contribute to the understanding of the two-dimensional circulation pattern in the central equatorial Pacific Ocean. Results from the 1977-78 contract year will provide valuable guidelines for modification of the instrument array for the 1979-80 FGGE year experiment.

4. Current status

Six bottom current meters and two bottom pressure recorders were deployed during leg 1 of the Tahiti Shuttle cruise. Stations were spaced in a horizontal array centered on the equator and 150°W, as shown in the accompanying diagram. The instruments were launched as free vehicles, with timed releases set to fire on leg 4 of that cruise, roughly 2-1/2 months later. All instruments were sucessfully retrieved and the data recovery rate is good. The data will be analyzed for possible Rossby waves, tides, inertio-gravity waves and "steady" bottom currents. These results should aid us in designing a bottom array for the 1979 FGGE year activity.

Equatorial Circulation Study NR083-343



Instrument array during 1977-78 Tahiti Shuttle cruise. All instruments were deployed as free vehicles on the bottom for about 2-1/2 months.

COMPUTATIONS OF THE NONLINEAR ENERGY TRANSFER
IN A GRAVITY-WAVE SPECTRUM

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Phone: 41 29 51

Dynamics of surface waves, numerical wave prediction, ocean models, ocean-ice-atmosphere interactions, climate dynamics.

The development of more efficient methods for the numerical integration of the Boltzman integral expression describing the nonlinear energy transfer within a surface-wave spectrum. The technique will be used to compute the nonlinear energy transfer for a wide variety of surface-wave spectra to provide background data for improved wave forecasts. These calculations can then be parametrised and incorporated in an improved wave prediction model.

The importance of nonlinear interactions for the evolution of the wind-wave spectrum has been demonstrated by JONSWAP (Hasselmann et al., 1973). These results have stimulated a number of new investigations of the Boltzman integral expression for the nonlinear energy transfer within the spectrum. While this work has helped clarify the structure of the Boltzman integral and has demonstrated the importance of shallow-water effects, all previous investigations have been limited to computations of the rate of change of the spectrum for special, idealized spectral distributions. For example, in all cases the directional spreading function was taken as symmetrical and independent of frequency and the frequency distribution as a single-peaked Pierson-Moskowitz, JONSWAP or similar spectrum. There is a need for more systematic computations of the rate of change of an arbitrary spectrum, with arbitrary, frequency-dependent directional distributions. There also exist no systematic investigations of the evolution of the spectrum under the influence of the nonlinear energy transfer, i.e. the Boltzman differential integral equation has not yet been integrated with respect to time. These types of investigations require considerable more computational efforts then have been expended on the problem to date, and can be meaningfully tackled only if a serious effort is made at simplifying the numerical integration procedure for calculating the Boltzman integral.

The initial goal of the investigation is therefore to develop a general purpose program for computing the nonlinear energy transfer within an arbitrary finite-depth, gravity-wave spectrum. The basic approach will be to compute the spectrum-independent part of the integral kernel only once and to store this on disc. The results can then be recalled for subsequent integrations for different types of spectra. The integration can be simplified by transforming to symmetrized integration variables which fully exploit the symmetry of the kernel. It is anticipated that the integration time for repeated integrations can be reduced in this manner by at least an order of magnitude.

The integration program has been completed and is in the final stages of debugging.

The project has only been running since June 1977, and it is therefore still too early to identify tangible results.

RESPONSE OF THE UPPER OCEAN HYDROGRAPHY TO WINDS

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206/543-5276

LONG RANGE OBJECTIVES: Study of the small scale processes occuring in the ocean, their relation to oceanic mixing, to water mass formation, and to external forcing.

PROJECT OBJECTIVES: Observe the effect of an early autumn storm on the surface mixed layer and evaluate the changes in water properties and fine structure which occur.

PROJECT STATUS: Conductivity temperature and depth (CTD) measurements taken on NOAA Ship OCEANOGRAPHER have been processed and a preliminary report distributed to cooperative investigators. Analysis of fine structure is proceeding.

Island Trapped Waves

Nelson G. Hogg

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This project is an outgrowth of a program to study mixing processes near boundaries and is a part of a long term investigation of the effects of bottom relief on water motions. The particular objects of this study are to observe trapped wave motions near Bermuda using current meter moorings and to understand the trapping mechanism in terms of simplified analytic and numerical models.

A three mooring array with Bermuda at the center of a large triangle was deployed for nine months in 1975. The resulting time series exhibit significant horizontal coherence at a number of discrete frequencies corresponding to periods ranging from 6.2 hr to 384 hr. At periods longer than inertial the estimated phases are consistent with wave motions traveling clockwise around the island. Shorter period results are more ambiguous but, apparently, both directions of travel are possible.

We have investigated the mechanism for trapping energy near a circular island with sloping sides. At periods greater than inertial perfect trapping is possible and the waves must propagate clockwise. At shorter periods the trapping is not perfect but energy leaks away at a rate which depends on the particular wave mode as well as other environmental parameters. Waves can travel in both directions.

This work is being prepared for publication and a second array of three moorings has been deployed in close to the island in order to look more closely at the dynamics of the trapping mechanism.

OCEAN WATER COLOR SATELLITE
UTILIZATION EXPERIMENT

Principal Investigator - Ronald J. Holyer

Naval Ocean Research and Development Activity
NSTL Station, Mississippi 39529
601-688-4864

Interest: Investigators interest is in the application of remote sensing technology to oceanographic problems with special interest in multispectral techniques.

Objective: Chlorophyll, sediment, and other consituents can give water masses characteristic colors which permit delineation of many of the same features that are observed in thermal images. Water color may yield clues about the origin and dynamics of upwellings, fronts, and eddies which would not be apparent from thermal data alone. Thus, the objective of this experiment is to demonstrate that remotely sensed ocean spectral reflectance (water color) is a useful interpretive aid in the study of the dynamic features of the ocean.

Approach: Data from LANDSAT, NOAA, and GOES satellites plus Ocean Color Scanner data from the NASA U-2 aircraft will be collected over the test area for the month of September, 1977. The experiment area is bounded by 37°N, 43°N, 127°W, and the California coastline. This time and location corresponds to SURVOPS 77 activities by the NAVOCEANO Sea Scan aircraft whose AXBT and ART data will provide ground truth for the satellite analysis. Data analysis will be performed on NORDA's Interactive Digital Satellite Image Processing System (IDSIPS). Comparison of our multispectral analysis with the analysis of DMSP thermal imagery by Dr. Bernstein of Scripps will achieve the stated objective.

Status: Data has been acquired and the interactive analysis system became operational in April 1978. We are ready to begin analysis.

RADIO MEASUREMENTS OF THE SEA SURFACE

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Phone: (415)497-3537

This is a joint venture between a group at Stanford and Dr. R. H. Stewart of Scripps. The long range scientific objective is the measurement of currents, current shear, wind speed and direction and sea state using remote sensing, i.e., radar techniques. A central feature of the joint work is the comparison of radar results with simultaneous oceanographic measurements with the goal of providing independent ship or shore based radar instrumentation to measure the above parameters.

We have recently completed an experiment which will produce comparisons of shore based radar with simultaneous spar buoy and pitch and roll buoy observations in the radar cell. Several publications discussing ocean surface current and directional spectra and a Ph.D. dissertation are presently in preparation.

Using much of the same equipment we are preparing to participate in the JASIN experiment in the summer of 1978. The radar will be installed on board the Woods Hole vessel Atlantis II for daily operation and comparison with the Scripps pitch and roll buoy and numerous other investigators' current, wind and spectra measurements.

The two major accomplishments of the year have been the completion of the Galveston Island synthetic aperture data analysis with a paper in the final stages of preparation and the completion of the Pescadero radar-oceanographic work. It is expected that the combination of Pescadero and JASIN results will produce a nearly complete understanding of what HF radar can and cannot do in oceanography.

CONTINUATION OF THE NORPAX SHIP OF OPPORTUNITY PROGRAM

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The long-range goal of the XBT project is to assure a continuous monitoring of the ocean's thermal structure such that quasi-synoptic charts can be produced depicting changes in the thermal structure. This would enable a derivation of changing patterns relative to heat content and heat advection which is necessary for scientific analysis of the large-scale processes of the ocean.

The objective of the project is to provide a continuous flow of high quality XBT observations from selected ships. The observations are to be distributed geographically so that a balanced data set is available to determine the ocean's thermal structure.

As a current status, the project is operating with twelve ships and is allied with several other similar projects that are operated by institutional/Federal Agency investigators, such as "TRANSPAC" "INDEX" "ISOS" and National Marine Fisheries Service.

Title: Entrainment Processes at Ocean Fronts

Principal Investigator: Takashi Ichiye

Institutional Affiliation: Texas A&M University

Mailing Address: Dept. of Oceanography, Texas A&M University,
College Station, Texas 77843

Telephone No.: (713) 845-6661

Long-range Scientific Objectives

(1) Dynamics of meso-scale circulation phenomena

(2) Incorporation of meso-scale phenomena into the general circulation as quasi-stochastic processes.

Objective of the Project

To study entrainment processes along the edge of the western boundary current, particularly, the Kuroshio theoretically and by field-experiments.

Current status of the Project

(1) A theoretical model of baroclinic instability for the shear flow was almost completed. In this model, the basic current has not only the vertical shear and stratification but also horizontal shear.

(2) The experiments for determining entrainment processes along the edge of the Kuroshio are planned. In such experiments, the principal investigator and a graduate student will participate in the cruise on board the Hakuho of Ocean Research Institute, University of Tokyo, about three weeks in September and October and will measure meso-scale current features with drogues and with a profile current meter.

Major Accomplishment

The new baroclinic instability model predicts strong instability waves with along-current wave lengths of 50 km. to 100 km. These waves correspond to scales of cold water blobs observed in the strong cyclonic shear zone of the Gulf Stream and the Kuroshio. The scheduled Hakuho cruise is specifically aimed to determine spatial structures of such blobs as well as their development with time.

Internal Wave and Mediterranean Water Front Studies

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My long-term research interests involve the experimental study of both internal gravity waves and small-scale mixing in the ocean and the formulation of simple mathematical models to aid in the interpretation of experimental results.

In the past two years ONR has sponsored two field experiments for me: a moored current meter array for internal-wave studies and a cruise south of the Azores in which a CTD was used to study a front-like transition in the Mediterranean Water near the mid-Atlantic Ridge.

Our recent studies of internal wave variability were to test a local interaction with the mean flow which would appear as a wave-induced vertical diffusion of mean flow momentum. Results do not support the magnitude of transfer recently predicted by Müller although some signature of coupling between the fields exists in regions of large eddy activity. Work on this problem will continue through 1978. In addition, some aspects of propagation and scattering of inertial-internal wave energy are being explored.

The recent CTD survey to the region near 35° N, 35° W has shown the existence of a front-like transition in the Mediterranean Water and suggests an interaction between the large-scale circulation and the ridge. Some simple physical arguments support the notion that the above two effects are coupled. This may be further explored with a simple advective-diffusive numerical model. The CTD data are still being processed but preliminary looks point to interleaving as a principle mode of salinity transfer across the Mediterranean water front.

LOW WAVENUMBER OCEAN ENERGY TRANSPORT

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Long Range Scientific Objectives: This study will concentrate on the very low wavenumber region of the ocean temperature turbulent spectrum; it will attempt to indicate the role played by large-scale ocean circulations as they function as possible energy sources for the remaining circulation scales of the spectrum. A comparison of the energy available in this scale will be made with energy amounts calculated in the higher wavenumber regions.

Project Objectives: Use computer program to obtain mass, salt and sensible heat transport across eleven latitude sections in the Atlantic Ocean which have IGY data. Describe seasonal variations, and relate computed results to energy calculations in other regions of the spectrum from other investigators.

Progress: Seven latitude sections have been processed (at 48, 40, 36, 32, 24, 16 & 8N) in the Atlantic Ocean; computations include transports to the ocean floor. An extensive study favorably compared available observed current values with calculated currents (Cummings' thesis). Transports within different watermasses flowing across these sections are being summarized, to be issued as a technical report in June 1978. Data cards for the four South Atlantic sections (8, 15, 24, & 32S) have been prepared and verified. Initial computation runs have been made for 8 & 15S, but several more will be required to establish the level of no motion. Bottom topographic data are available along these sections, to be used in extrapolating the flow field downward from the deepest ocean observations. A manuscript in preparation will summarize project results and compare them with values of smaller (including meso-) scale eddy transports of others.

Major Accomplishments: Cummings, Walter J., 1977. A Description of the General Circulation in the North Atlantic Ocean Based on Mass Transport Values Derived from IGY (1957-58) Temperature and Salinity Data. Master's Thesis, Dept. of Oceanography, Naval Postgraduate School. 134 pp.

Jung, Glenn H., 1976. New Calculations of Heat Transported Poleward by Ocean Currents. Paper presented at AGU Fall Annual Meeting, San Francisco, December 1976.

Jung, Glenn H., 1977. Ocean Energy Transport Anomalies During the Sunspot Maximum of the IGY (Autumn 1957). Paper presented at the AGU Annual Fall Meeting, San Francisco, December, 1977.

CURRENT SHEAR ACROSS AN OCEANIC FRONT

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Long-Range Scientific Objectives

Our study of the near surface oceanic fronts persistently found in the sub-tropical convergence zone of the Sargasso Sea is to be able to understand and eventually predict the causes of intensification and the conditions for instability of these fronts.

Objective of the Present Project

Field observations were made in March 1976 from the R/V RESEARCHER in a frontal region south of Bermuda. Dr. Ants Leetmaa of AOML made CTD observations on a scale of several hundred kilometers in order to study the relationship of the surficial fronts with the meso-scale motions of the main thermocline, while we towed a combined CTD and current measuring system horizontally across the fronts. Our objective was to evaluate the stability of the frontal surface.

Present Status

Horizontal current shears were measured on several crossings of the front and these are being compared with the predicted shear computed from the measured density discontinuity across the front. In the few instances that a well-developed front was observed, the shear was either equal to or several times larger than predicted. The width of the shear zone was measured, perhaps for the first time, and found at times to be less than a kilometer wide, compared to 100 m for the density discontinuity.

Detailed analysis of the performance of the acoustic back scattering current system during the cruise indicated the need for improvements. An engineering field test was conducted in January 1978 and design work has been initiated.

OBSERVATIONS AND ANALYSES OF INDIAN OCEAN EQUATORIAL CURRENTS

Robert A. Knox
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One of my scientific interests, the one which lies behind this project, is the time-dependent circulation in the equatorial oceans. The principal feature which distinguishes the equatorial region from midlatitudes is the rapidity of baroclinic adjustment to variable wind stress via equatorially trapped waves (Moore and Philander, 1977).

This project has had as its objectives the observation of selected aspects of the time-dependent equatorial circulation in the Indian Ocean, and, during the past year, some theoretical studies of interactions between equatorial waves and mean flows. The observational effort has been to maintain moored current meters at the equator north of the Seychelles long enough to assess the importance of seasonal (monsoon-driven) fluctuations at intermediate depths (500 m). Such fluctuations dominate the near-surface record (Knox, 1976). This effort is about to end, and the data will be analyzed in the coming year. An example of data gathered already, although too short to address monsoon phenomena, contains some interesting higher frequency information. Spectra (not shown) indicate that energy in the meridional component (v) exceeds that in the zonal component (u) at periods between 100 and 1000 hrs; this argues for dominance of modes with latitudinally symmetric v-fields, of which the gravest is the Yanai wave. Similar results at similar depths have been obtained in the Atlantic by Weissberg, Miller and Knauss (1975).

The theoretical work, largely due to M. McPhaden, a graduate student, has utilized a simple two-layer equatorial β-plane model with various prescribed, geostrophically balanced mean zonal flows in the upper layer. A linear stability analysis reveals neutral oscillations corresponding to what would be the classical free modes in an ocean without mean flows. The mean flow induces changes in the mode frequencies and structure; the principal effect is to distort u, while hardly changing v or the pressure (sea level) field. Thus measurements of zonal velocity as a function of latitude, not presently available in sufficient detail, would provide a much more sensitive test of the importance of wave-mean flow interactions than would island sea level records, which have been used to identify equatorial modes (Wunsch and Gill, 1975).

a. Ocean Mixing Processes
Richard B. Lambert, Jr., Principal Investigator
Science Applications, Inc.
8400 Westpark Drive
McLean, Virginia 22101
703/827-4752

b. Long Range Scientific Objectives of Principal Investigator

To understand ocean microstructure, small scale mixing processes, and their relation to mesoscale and large scale ocean circulation and energy budgets.

c. Project Objectives

1. Analyze hydrographic data from oceanographic cruises on R/V TRIDENT, TR-151 and 135 in terms of lateral and vertical mixing in the Gulf Stream front.
2. Analyze laboratory data and historical ocean data in terms of the mean T-S properties of the ocean and their relation to double-diffusive transport mechanisms.

d. Current Status of Project

1. Abstract published in EOS 59(4), p. 301: "Extrainment and Mixing in a Gulf Stream Meander"
2. Paper "Transport Processes Across the Gulf Stream" to be submitted to Journal of Physical Oceanography in June, 1978.
3. Paper relating Double Diffusion to mean T-S properties to be submitted in September, 1978.

e. Data from TR-151 clearly show interleaving of 18^{O} Water from the Sargasso and Slope Water underneath the core of the Gulf Stream.

SMALL SCALE OCEANIC FEATURES

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Scripps Institution of Oceanography
La Jolla, California 92037

Phone: 714/452-3234

Long Range Objectives: An understanding of the levels of oceanic mixing in the vertical, and advection and mixing in the horizontal is sought. The variability (temporal and spatial) of physical and biological properties of the ocean is desired, to understand the propagation of heat, mass, momentum and biota, and their interrelationships with each other and with larger scale motions of the ocean.

Project Objectives: An investigation of the fine and microstructure in the temperature and velocity fields has been investigated in the MILE experiment through the use of a large, free-fall vehicle, during and after the passage of a storm. The nature of the entraining layer at the base of the mixed-layer will be investigated for the effects of stirring and suppression by buoyancy forces to determine the mixing efficiency, and downard propagation of energy of such events. Concommitantly, the use of a slow-fall XBT is being examined for possible use as an expendable fine to microstructure survey tool.

Status of Project and Accomplishments: Twenty-six successful drops were made in the MILE experiment, under conditions ranging from 40 knot winds to calm seas and clear skies. This data is presently under analysis. A persistent and sometimes turbulent shear layer was observed at the base of the mixed layer, and was relatively thin--from 1 to 3 meters thick. Deeper within the thermocline, the levels of velocity structures were immeasureably small. Due to the catastrophic loss of the free-fall vehicle in a shakedown cruise in preparation for the POLYMODE Local Dynamics Experiment, the effort for developing an expendable fine structure profiler is being vigorously pursued.

DEFINITION OF OCEAN SURFACE CURRENT BOUNDARIES USING SYNTHETIC APERTURE RADAR OVER THE TAIL OF THE GRAND BANK

Principal Investigator - Paul E. La Violette

Naval Ocean Research and Development Activity
NSTL Station, Mississippi 39529
601-688 4864

Interest: The long-range scientific objectives of this experiment is to explore and exploit the use of remote sensing instruments for oceanographic purposes.

Experiment Purpose: The main purpose of the present experiment is to show (a) that surface currents modify the amplitude and/or orientation of local waves to form surface patterns with definable boundaries and (b) that the diffuse return of aircraft and satellite SAR's can delineate these patterns and boundaries. If successful, the results of the experiment will show that SAR-derived patterns of wave conditions can be used as an all-weather tool to derive the oceans surface circulatory.

Experiment Plans: The region of study for the experiment is an area off the coast of Newfoundland called the Tail of the Brand Banks. Satellite, aircraft and ship data will be collected in the area during two phases of the experiment. The first phase called "Baseline," will occur in June 1978; the second phase, called "New Look," will occur in May 1979. To provide continuity between the two phases, satellite data will be collected for selected seasonal months.

Major Accomplishments: Experiment is in pre-survey stage at this time. No major accomplishments.

STUDY OF THE MECHANICS OF MOMENTUM, WATER DROPLETS, MOISTURE, AND HEAT TRANSFER AT THE SEA-AIR INTERFACE UNDER HIGH SEA STATES

Principal Investigators: Dr. S.C. Ling and Dr. T.W. Kao
Institution: The Catholic University of America
Dept. of Mechanical Engineering
Washington, D.C. 20064

Telephone: 202-635-5170

Our long range objective is to study the extremely complex problem of sea-air interface through a step by step plan of theoretical analyses, controlled laboratory studies, and field experiments. These steps will be repeated until a satisfactory analytical model is obtained. Particularly, we are interested in the production of water droplets by whitecaps and sea sprays, because the evaporation of droplets creates a strong latent heat sink which in turn enhances the vertical transport of moisture and heat from the ocean. In addition, we are interested in the mechanics of the wind on the breaking waves, because wind drag on waves produces a surface drift which in turn causes wave breaking, air entrainment, and turbulence. The turbulence in turn enhances the transport of heat through the sea surface layer.

Our first objective is to understand the complex mechanics of the atmospheric surface layer and then the mechanics of the sea surface layer. From this knowledge we eventually hope to treat the two layers as a one coupled system.

Currently we have succeeded in developing a perliminary analytical model that will account for the inter coupling effect of the wind, temperature, humidity, and water droplet fields. We have also developed an accurate water droplet size-concentration detecting system for application over the ocean. The system has been proven for high sea state application during the 1977 JASIN experiment. We are currently equipping for the coming 1978 JASIN experiment which will involve three extensive cruises over the North Atlantic Ocean. Complete soundings of wind, temperature, humidity, and droplet size concentration will be made to verify the analytical model.

Our major accomplishments can be briefly summarized as follows:

1. Developed an accurate droplet size-concentration detecting system.
2. Discovered that the droplets produced by breaking waves have a universal normalized size distribution.
3. Proven that 30-200μ water droplets are a major source of moisture for the atmosphere. Their latent heat sink promotes transfer of heat from the sea.
4. Developed a realistic model for the atmospheric surface layer, from which accurate estimate for the transport of heat and moisture can be made.

Equatorial Jets in the Indian Ocean (INDEX)

James R. Luyten

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Woods Hole MA 02543

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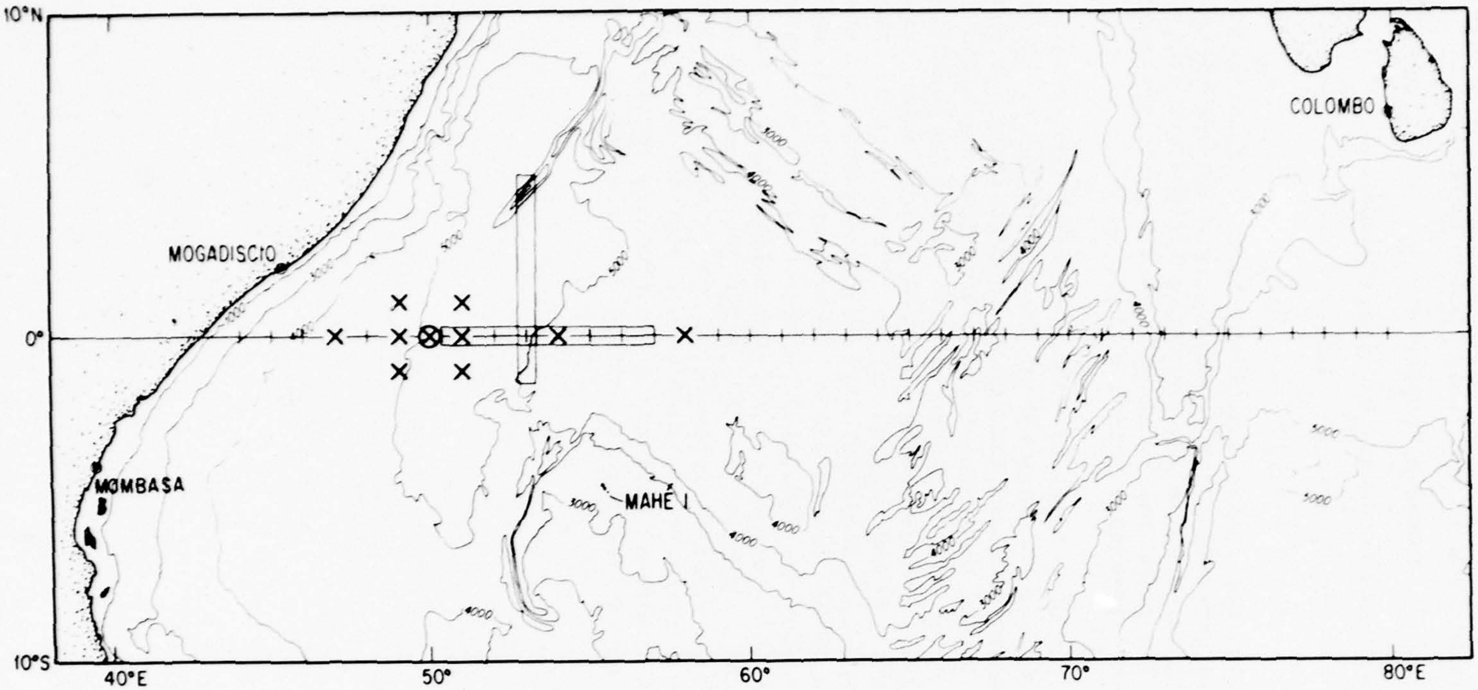
The long range scientific objectives of this investigator are to observe and understand the processes by which the energetically dominant large-scale low-frequency motions are excited and maintained. The principal techniques used to date are moored instrumentation and free-fall velocity profiles.

The scientific objectives of this particular program are to explore and rationalize the response of the equatorial ocean to the large scale meteorological forcing at long periods. In the Indian Ocean the annual Monsoonal forcing dominates the steady winds and drives a variety of phenomena with annual periodicity. An exploratory experiment involving a moored current meter array and intensive profiling was carried out in 1976 as part of INDEX. This experiment provided the first data on the structure of the velocity field below 200 meters depth. The velocity field, during the Southwest Monsoon, was dominated by several zonal sub-surface jets trapped near the equator, roughly 100 meters thick. The current meter array showed that the 200 meter jet broke down in mid July although no event was observed in the wind field. The statistics of the current meter array show a westward intensification at low-frequency near the African coast, together with a dominance by variability at periods of the order of 40-60 days.



INDEX - 79 EXPERIMENT

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× WHOI MOORING - CURRENT METERS AT 200, 500, 750 METERS

□ INDEX - 76 EXPERIMENT

W.H.O.I.
LUYTEN

Analytical Modeling of the Large-Scale Temperature Fluctuations in the North Pacific

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Long-range scientific objectives of the Principal Investigator: Development of theoretical models for fields of large-scale and meso-scale waves and turbulence in the ocean with application to field data (mainly from the North and Equatorial Pacific) in order to understand and predict fluctuations of temperature, sound velocity and currents in the ocean, especially in the upper ocean.

Objective of the project: Analysis of temperature data (XBT and hydrographic data, time series of monthly mean values up to 20 years) from various parts of the North Pacific by means of model fitting (cross spectral fit). Development of models, especially baroclinic Rossby wave models in case of non-vanishing mean shear flow. Study of generation of observed processes (from the temperature analysis), especially by local meteorological forcing. This project is part of NORPAX.

Current status of the project: The development of baroclinic Rossby wave models has been completed. We are presently preparing the application of these models to the TRANSPAC data which are being collected under the NORPAX program in the area 30°N to 50°N, 170°E to 150°W. The application of our theory of local meteorological forcing to oceanic and meteorological data from an area between Hawaii and California has almost been completed.

Major accomplishments: We have found that, for time scales between about 1 and 10 years and lengths scales between about 1000 and 3000 km, first order baroclinic Rossby waves appear to dominate the internal temperature fluctuations in those parts of the North Pacific between 20°N and 50°N where the mean current is negligible. For the area of the North Pacific Current, we have determined the shear modes of velocity and temperature. Our Rossby wave model to be fitted to the TRANSPAC data is composed of these shear modes. Our studies of the possible local meteorological forcing of the Rossby waves, we determined from temperature observations between Hawaii and California, have reinforced our opinion that the buoyancy flux at the sea surface plays a significant role in the generation of these waves.

TURBULENT DECAY - Subtitled - Dynamics of Rotating and Non Rotating Intrusions and Internal Solitary Waves - Tony Maxworthy, University of Southern California, Department of Aerospace Engineering, Los Angeles, California 90007, (213) 741-6240.

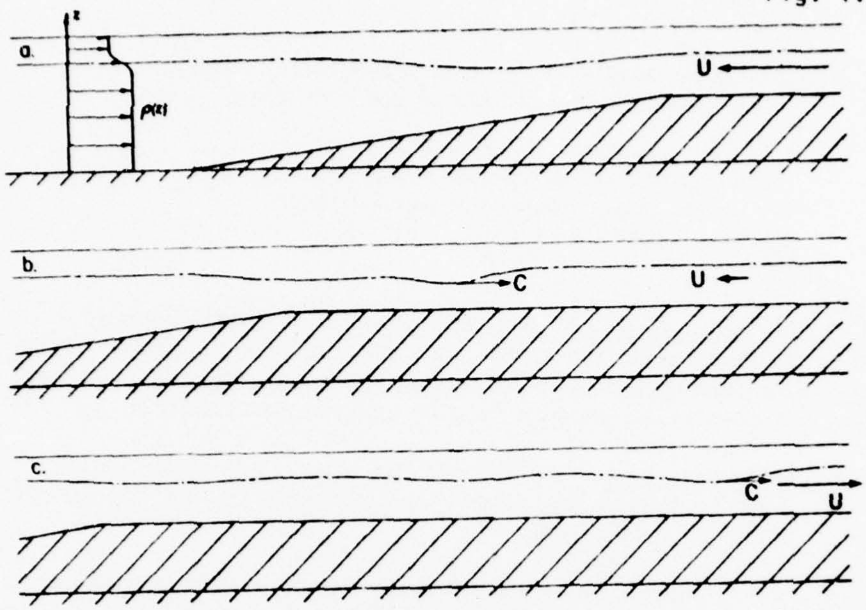
b) To understand the role played by internal solitary waves, intrusive motions and double diffusion in the dynamics of the world's oceans.

c) To determine various mechanisms whereby internal solitary waves can be generated in a stratified fluid, how these solitary waves interact, promote mixing and transfer energy to various scales of motion and how they are related to the dynamics of intrusions.

d) We are currently undertaking a series of laboratory experiments on the generation of solitary waves from the gravitational collapse of mixed regions and by tidal flows over submarine topography. Two papers on some aspects of these subjects have been prepared and submitted for publication. However, since this is a new project no papers have appeared in print yet. We are continuing experiments on wave generation and turbulence decay in a stratified fluid, wave generation by tidal flows and the instability and flow field of stratified eddies in a rotating fluid.

e) We have isolated the mechanism whereby solitary waves, as observed over the Continental Shelf, can be generated by tidal flows (see fig. 1) and a paper on this subject has been submitted. We have also performed experiments on the three dimensional interaction between solitary waves and are able to explain sone of the features seen in satellite picture of such interactions (see fig. 2).

Fig. 1.



Generation of internal solitary waves by tidal flow over submarine topography. a) The ebb tide generates a depression which propagates onto the shelf as the tide slackens. b),c) The evolution of this disturbance is characterized by the generation of a train of solitary waves, the number and amplitude of which can be related to the form of the initial disturbance.

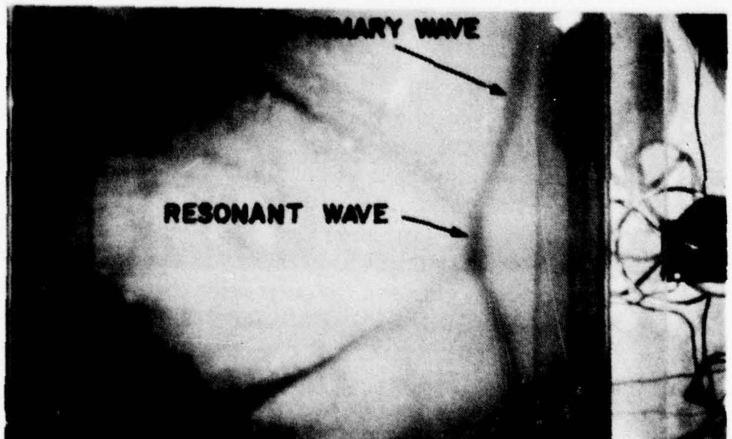


Fig. 2

Interaction of two solitary waves at an angle showing the generation of a third wave between them by resonant interaction. Many satellite observations show an identical interaction over the Continental Shelf.

THERMOSTADAL ANALYSIS OF THE UPPER WATER MASSES AND CIRCULATION OF THE WORLD'S OCEANS

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Long-range scientific objectives: The principal investigator's objective is to determine the modes of formation and renewal of the main thermocline and upper deep waters of the world's oceans, and to understand their relationship to the general circulation.

Present project objectives: To define the specific large volume "mode waters", their formation sites, and circulation paths, by the thermostadal analysis technique.

Current status: A paper has been published on a southern hemisphere 18° Water-like family of water masses called subantarctic mode water (Deep-Sea Research, 1977). Two additional topics briefly discussed at the end of this paper have been further studied, and two papers are nearly ready for submission. These deal with a new hypothesis for antarctic intermediate water renewal and with the recirculation of subantarctic mode water within the southern hemisphere subtropical gyres.

Work is underway on a description of the pycnostad distributions in the north central and northeast Atlantic.

Major accomplishments: A new perspective is emerging on the origins of the main thermoclinic and intermediate waters of the world's subtropical gyres. A single process has been found to be responsible for the dominant large volume central waters of these gyres. This is vertical convection on the poleward side of the gyres in a relatively restricted area, which gives, through its vertical homogenization, a narrowly defined temperature-salinity correlation over a large depth range--a pycnostad. These pycnostads recirculate in the gyres following the geostrophically balanced large-scale circulation, with little further alteration of charcteristics. This is then a variation on the Iselin (1939, Trans. Amer. Geophys. Un., p. 414-147) mechanism, with cross-isopycnal mixing dominating in the region where isopycnals outcrop, and with few specific high volume modes dominating the temperature-salinity correlation.

STUDIES OF EQUATORIAL DYNAMICS

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(with D.W. Moore)
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I am interested in low frequency (periods greater than the local inertial period) and large scale (periods greater than the local Rossby radius of deformation) oceanic changes. Recently, I have concentrated my modelling efforts to the equatorial oceans in order to investigate its response to changes in wind stress. In the near future, I intend to extend this work. In the next decade, I hope to participate in a joint French-American project to study long term changes in the thermal structure of the equatorial Atlantic.

Many of the models now being used to study the equatorial ocean can, to a large extent, be described in terms of linear dynamics. Solution of these models compare favorably with observations of equatorial adjustment in the Indian, Atlantic and Pacific Oceans. The objective of my part of this project is to study how non-linearities alter these linear solutions.

In particular, Dennis Moore and I are considering the effect of non-linearities on an internal equatorially trapped Kelvin wave. We have considered the problem within the framework of the simple two-layer model, and are now extending the study to apply to the more realistic (and mathematically more difficult) continuously stratified model.

The results from the two-layer model show that there is surprisingly little effect on the Kelvin wave. However, there are suggestions that a larger change is possible in the continuously stratified system.

TITLE: SATELLITE-TRACKED DRIFTING BUOYS

PRINCIPAL INVESTIGATOR:

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La Jolla, California 92093
714/452-3965

LONG-RANGE GOAL

The long-range scientific goal of this study is to understand processes responsible for the intermediate and large space and time fluctuations in the surface currents of the North Pacific. The approach utilizes the position fixing and data transmission capabilities of satellites, particularly NIMBUS-6. The mesoscale and large scale fluctuations may play a decisive role in the performance of long-range, undersea surveillance systems. They also are important in avoiding detection of our own FBM submarines.

OBJECTIVES OF PROJECT

The specific objective of this project is to provide by means of satellite tracked drifter buoys the near surface circulation data of the North Pacific.

CURRENT STATUS AND PROGRESS

Following the first pilot study deployment of drifting buoys in October 1975, three major deployments were made as part of NORPAX's Anomaly Dynamics Study (ADS); 16 in June 1976, 16 in September 1976 and 19 in June of 1977. Data returned from the first two of these deployments provided our first realization of the near surface circulation in the mid-latitude eastern North Pacific. This realization shows a large seasonal signal with winter speeds four times those observed in the summer and early fall. This seasonal signal is closely correlated with the overlying wind field. The drifter data indicates a surface flow extending to a depth of some 30 meters at 30° to the right of the wind. Sixteen of the nineteen drifters deployed in June 1977 are still operational. When complete, these data, together with those of the first two deployments, will allow an investigation of the interannual variation of circulation.

MAJOR ACCOMPLISHMENTS

Demonstration that the drift buoy system designed for this program can survive and operate in the harsh environment of the mid-latitude North Pacific.

PUBLICATIONS

The following papers are to be submitted to the Journal of Physical Oceanography in April 1978:

1. Analysis of surface current response to wind forcing.

2. The near surface circulation of the eastern North Pacific.

3. Wind drag and relative seperations of undrogued drifters.

Title: The Upper Ocean Response Study

Investigator: Dr. M. Miyake
604/656-8277
Institute of Oceanography
University of B.C.
Vancouver, B.C. Canada
V6T 1W5

The Long-range Objectives

Identification and understanding of the relevant physcial processes for modification of the upper ocean thermo-structure. The inclusion of the effect of horizontal advection is most important. The study is based on the diagnostic analysis of the upper ocean temperature of the North Pacific.

The Objective of Project

Task I-AXBT Survey of the North Pacific-NORPAC-ADS

Through bi-weekly AXBT surveys of 10° latitude and 5° longitude area centered around 45°N 165°W, with P3 aircraft based at Adak, the thermo-field of the upper 300 m. is mapped. Analysis will consist of assessing the relative role of surface transfer of heat (including radiation) vs. advection process. The processes relevant for transformation of large scale thermo-anomaly fields (determined through the Transpac Data) is examined as their boundaries propagate through the AXBT sampling region.

Task II- Meso-scale dynamics in "Mixed Layer Experiment"

Short time response and space variation of thermofield of the upper ocean is obtained around Station P through the AXBT survey. The STD survey was carried out within a 30 mile tri-angular area. Time variation of meso-scale structure is assessed along with the mixed layer evolution due to atmospheric forcing events.

Current Status

1. ADAK-AXBT Survey.

   Bi-weekly P3 flights started March, 1977, and continue today. Data is put in data summary and distributed. Scien-tific analysis consists of assessment of atmospheric forcing and evaluation of the consequences of subsurface anomaly.

2. Meso-scale Dynamics in MILE

   Geostraphic velocity is computed from meso scale STD survey. Advection of temperature field is being assessed for time evolution of thermo field.

Major Accomplishments

Meso-scale Dynamics in Mile. Only half of the heat content of the upper ocean is controlled by atmospheric forcing for the MILE period (7 weeks, Aug.-Sept.'77). As much as half depends on the advective process. Inertial -gravity wave forced by atmo-spheric forcing events also creates an artifical deepening for a two or three day period.

OCEANOGRAPHIC USES OF SATELLITE INFORMATION

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Long Range Scientific Objectives of the Principal Investigator: Description of dynamics of nonlinear wave phenomena, with a view towards their effect on exchange, mixing and current formation. Description of some of the features of random waves and turbulence in terms of a field of wave packets. Uses of observations of waves to infer other properties and variables in the ocean.

The Objectives of the Project: To assess the uses of satellite information in research on dynamic oceanography. To generate examples of such use and to formulate recommendations and suggestions for the better utilization of satellite information.

The Current Status of the Project: Funded for another year as of January 1, 1978, according to notice recently received. Work continuing on data acquisition and analysis, and the writing of papers. One graduate student, A. Mascarenhas, Jr., working on his master's thesis, expected to be completed in summer 1978.

Major Accomplishments: A theoretical explanation of cusped frontal waves in equatorial Pacific Ocean, as observed by Legeckis. The waves may be geostrophic billows and the observation suggested that a theoretical solution be sought, and this was done.

Observation of apparent edge waves inshore of Loop Current in Mexican Gulf, and a theory worked out for finite amplitude rotational edge waves, a new theoretical solution.

Primer on Oceanic Fronts

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The long-range scientific objectives of the principal investigator are to understand the dynamics of oceanic fronts, and their role in other oceanic and in air-sea interaction processes.

The objective of the project is to provide naval management with a cogent summary of contemporary knowledge about oceanic fronts.

The primer is in the second draft stage.

The Chapman Conference on Oceanic Fronts was convened in New Orleans on 11 to 14 October 1977. It was attended by about 200 people and about 80 contributions were made. A summary of the Conference has been written and accepted for publication in the May 1978 issue of EOS, The Transactions of the American Geophysical Union. Also, the Journal of Geophysical Research is planning to publish about two dozen papers stemming from the Conference in a 1978 issue.

Project Title: "Studies of Equatorial Dynamics"

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Long-Range Scientific Objectives

My long-range scientific objectives center on theoretical modeling of oceanic circulations, using primarily analytic (as opposed to numerical) techniques. The present focus of my work is modeling of time-dependent equatorial circulations, as a response to time-varying surface forcing.

Objectives of the Project

The objectives of the project are to model both steady and time-dependent equatorial flows, and to understand how they are driven by the atmosphere and in turn influence the atmosphere. Specific objectives include understanding non-linear effects on Kelvin waves, developing new undercurrent models, and understanding the cause of the multiple "undercurrents" observed by Luyten and Swallow in the equatorial Indian Ocean.

Major Accomplishments

Major accomplishments within the last few months include the submission of three manuscripts for publication and the completion (with J. McCreary) of a one and a half layer model for studying non-linear effects on equatorial Kelvin waves. This work, although based on a naieve perturbation expansion, leads to an elegant analytic treatment which gives a very simple description of the effects. This work is now being written up.

HYDRODYNAMICS OF THE OCEAN SURFACE LAYERS

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The long-range objective of this project is to understand the hydrodynamics of the variability of the temperature, salinity, and velocity fields of the upper layers of the oceans. Presently, there is a strong emphasis on gathering and interpreting field data on upper-layer velocity field and temperature variability on a time scale of a few minutes to a few days. In central ocean gyres, the modeling hypotheses of one-dimensional vertical heat, momentum, and turbulent energy are tested, and initial field experiments are planned to describe and understand the simplest two (and three) dimensional modifications of the upper-ocean variability. Specific plans include study and description of the mixed-layer, wind-forced response and the description of the internal wave field in the upper layers at Ocean Station PAPA. The data base for this study comes from a vertically densely instrumented single point surface mooring of VACM's. We also plan to study the ocean surface circulation near the western North Pacific Subtropical Front. Surface drogues will be deployed in this frontal area. We plan to describe the mesoscale ocean conditions and convergence on both sides of this front.

Over the past two years, we completed the study of the one-dimensional models of the seasonal thermocline in the North Pacific. We showed that the seasonal cycle of the vertical distribution of heat at both Ocean Stations PAPA (150°N, 140°W) and November (30°N, 120°W) can be adequately described with a single, bulk model for the ocean mixed layer and a weakly diffusive, continuous model for the seasonal thermocline. The conditions at Ocean Station Victor (30°N, 120°E), however, cannot be described with the model which applies so well to the eastern North Pacific. At Victor, the processes which distribute heat in the seasonal thermocline are intense. This study points out that the theory of vertical transfer in the seasonal thermocline is the weakest link in upper ocean models. A set of 19 day records of temperature and horizontal velocity field was obtained from Ocean Station PAPA during late summer of 1977. Below a surface toroid, twenty VACM's were placed on 3 m intervals from 5 m to 42 m depth and at 7 to 50 m intervals from 42 m to 125 m. The analysis of these records is presently the principal research topic. Initial results show that the principal temperature variability in the seasonal thermocline is primarily due to an energetic, semi-diurnal, internal tide and that the velocity field variability is due to inertial motions. The internal wave energy does not extend out to the local thermocline Vaisäla period, but is sharply cut off at the deep water Vaisäla period.

We studied the general relationship of the wind-field to the dynamic topography in the North Atlantic. New dynamic topography charts of the North Atlantic were published. Both a Sverdrup regime and a re-circulation regime were identified. The large-scale, general circulation of the oceans is a long-standing research topic of interest, and dynamically consistent descriptions of the persistent ocean circulation were pursued under ONR sponsorship for the past 15 years.

Research in Mesoscale Atmosphere and Ocean Interaction
Ocean Forecasting

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Long-range Scientific Objectives

The long-term scientific objectives of this investigator encompass the utilization of numerical models of physically realistic upper ocean circulation to demonstrate our understanding of physical processes in the ocean.

Objective

We wish to discover once and for all in a five-year research project whether or not we can actually construct a useful model of the circulation of the ocean in a limited region (1000 km square) on the time scales of several days to a few months. The project will sort out the various basic research problems which need to be solved to integrate with some measureable success a baroclinic ocean of 1000 km square embedded in a coarse grid (x=200 km) climatological model the size of an ocean basin. At the present time the project is developing a complete model of the equatorial ocean circulation to test hypotheses regarding El Nino.

Current Status of Research and Progress

Final coding of the El Nino model is being completed by Kindle. Camerlengo and O'Brien are finalizing a paper on open boundary conditions to be sent to *J. Comp. Phys.* Three papers with Dennis Moore on the Gulf of Guinea seasonal upwelling have been completed. A multi-dimensional model of ocean circulation with emphasis on bottom-trapped Rossby modes is under development by Suginohara. A review of errors in ocean models is being prepared.

Major Accomplishments

A linear model on an equatorial β-plane has been integrated over a 120 day period in a basin that approximates the tropical Atlantic ocean. An increase in the westward wind stress of 0.025 N m^{-2} in the western Atlantic excites an equatorially trapped Kelvin wave that propagates eastward along the equator, moves poleward at the eastern boundary, and produces upwelling throughout the Gulf of Guinea. Non-linearities are shown to have the effect of amplifying the effects of the Kelvin wave and prolonging the upwelling event. It is shown that local winds cannot account for the seasonal upwelling in the Gulf of Guinea.

STUDIES OF MICROSTRUCTURE

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Long-range scientific objectives: To understand the role of turbulence in determining the circulation and the distribution of salt and heat in the ocean.

Project objectives: There are at present two projects:
(1) Studies of Oceanic Energy Dissipation.
The objective is to relate estimates of the energy dissipation from our free-fall measurements of small-scale (1-50 cm) velocity fluctuations to the mean fields of velocity and density.
(2) Spatial Scales of Oceanic Turbulence.
Three identical free-falling instruments have been used to collect simultaneous profiles of temperature and temperature gradient at varying horizontal separations. The objective is to determine and relate the horizontal and vertical scales.
(3) Distribution of Oceanic Turbulence.
Work is beginning on a simple disposable instrument for large-scale oceanic sampling and extensive geographical coverage.

Current status:
1. Energy dissipation studies - Three major cruises have been made with the instrumentation. Results from one are in press, results from a second are submitted and the results from the third are in preparation. A new instrument is being built to replace the one which is now worn out. Development of the velocity probe is under way to simplify construction, improve the response characteristics and ease the calibration procedure. Work is also under way toward explaining the dynamic response of temperature sensors as well as temperature sensors heated for anemometry purposes.

2. Spatial scales - Data taken by our free-fall instruments in Howe Sound - a local fjord - are being analyzed along with STD, current meter and water bottle samples. The analysis is relating the temperature microstructure to the deep flushing which was also observed in the basin.
Data collected along the Equatorial Atlantic have been analyzed for information about the spatial extent and the relation of the temperature microstructure to the local dissipation rate. A paper is in preparation.

Major accomplishments:
1. Development of a useful velocity sensor and support system for measuring oceanic velocity microstructure.
2. Measurement of dissipation rates associated with the Atlantic Equatorial Undercurrent and their relation to the energetics of the region.

3. Measurements of dissipation rates near the Azores which showed high dissipation rates at the base of the thermocline, as well as providing statistics for the upper 800 m of the ocean.

4. Measurements of velocity microstructure in a variety of oceanic environments as a part of the Fine and Microstructure Experiment (F.A.M.E.).

5. Theoretical explanation and measurements for thermistor response (Deep-Sea Research, October 1977).

AIR-SEA INTERACTION

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Long-Range Objective.

- To gain a better understanding of physical processes in the upper ocean and their relation to atmospheric forcing.

Objectives.

- To determine the characteristics of temperature and conductivity fluctuations in the upper ocean and their relation to surface winds and heat transfer.

- To investigate mechanisms of mixing in the upper ocean.

Current Status. We have completed analysis of temperature, salinity, wave height and radiation measurements made from the R/P FLIP. In cooperation with R. M. Mesecar and the Technical Planning and Development Group, we constructed a towed thermistor chain system which was used during the Mixed Layer Experiment (MILE). We are currently analyzing the 60 hours of data collected during this experiment. We will construct cross-sections of the temperature field, compute spectra, investigate the characteristics of internal waves and examine mixing processes. We will also use the towed thermistor chain in the Joint Air-Sea Interaction Experiment (JASIN) from mid-August to mid-September 1978. Our measurements will be closely coordinated with those of M. Briscoe of WHOI.

Accomplishments

- Evaluated several formulae for estimating radiative transfer over the ocean by comparing them with observations.

- Discovered that warm sea-surface temperatures are positively correlated with the upwind slope of dominant surface gravity waves and with the steep downwind slope of shorter gravity waves.

- Discovered an increase in the slope from the expected -5/3 of atmospheric temperature spectra at frequencies just below the frequency of the maximum dissipation of temperature fluctuations. The increase in slope occurs at the same non-dimensional wave number as for temperature spectra in the upper ocean during high winds.

OCEAN WAVE MEASUREMENT BY ANALYSIS OF RADAR IMAGES OF THE OCEAN

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Long-Range Scientific Objective: Our overall, long-range objective is to discover and develop radar techniques which can make meaningful measurements of waves and currents over large ocean areas. Further, our intention is to demonstrate each technique as a useful research tool by applications to current problems in physical oceanography. These applications are made in collaboration with the oceanographic community. In pursuit of these goals we have employed radar wavelengths from centimeters (microwaves) to over a hundred meters (HF) with platforms on land and sea as well as aircraft and soon SEASAT-A. Our work has ranged from data collection hardware to data processing and interpretation.

Objective of this Project: Because they can gather wave data over large ocean areas at frequent time intervals, radar techniques are well suited to the study of problems in ocean wave generation, propagation and interaction with coasts and islands. High resolution ($\sim$10m) synthetic aperture radar (SAR) images of the ocean surface show great potential for studies involving such phenomena as ocean waves, current gradients, slicks, rainfall and internal waves. However, quantitative interpretation of SAR images in terms of ocean wave directional spectra $\Psi(k,\theta)$ is presently very limited. Our objective here is to i) investigate the basic radar wave - ocean wave interaction mechanism, ii) develop a mathematic model of the interaction and, iii) use this knowledge to construct and apply algorithms to quantitatively measure Ψ from SAR images. Applications involve SAR images and surface truth obtained during the 1977 West Coast Wave Experiment and close collaboration with Drs. R.H. Stewart of Scripps and O.H. Shemdin of JPL.

Current Status of the Project: Since this reseach began in November 1977, it has become evident that much can be learned regarding SAR image interpretation by comparing estimates of Ψ, based on very simple assumptions, with surface truth measurements. Hence our major efforts are now going into software developments which will allow us to make crude estimates of Ψ given a SAR image. The image digitization process is in hand and the implementation of a two-dimensional Fourier transform of the digitized image is now underway using a special purpose FFT computer. This capability will be focussed on the comparison of SAR and surface truth data obtained during the 1977 West Coast Wave Experiment. Arrangements are being made to obtain SEASAT-A SAR images and surface truth measurements during the 1978 JASIN experiment off Scotland.

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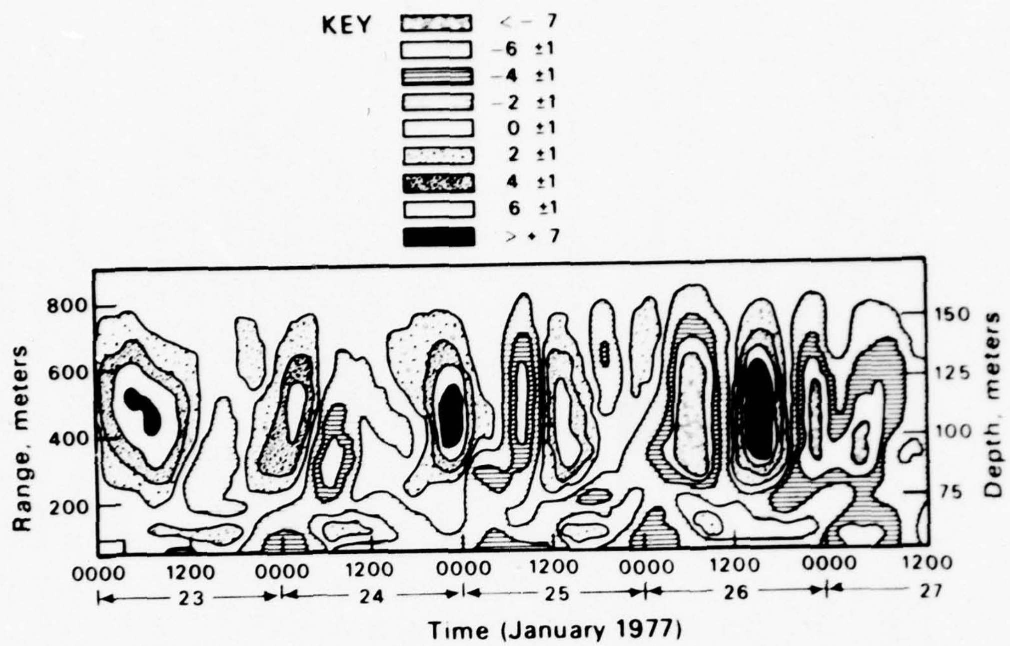
b) Better understanding of mid-scale oceanic processes, in particular the dynamics of the upper ocean internal wave field, is the objective of this program. The approach has been characterized by ongoing efforts to construct open ocean measurement arrays of sufficient size and sensor density to resolve the spectrum of the motions, as opposed to the more general (and ambiguous) practice of fitting parameters of a preconceived model to a more limited data set. Observations of the energy fluctuations in specific bands of the internal wave spectrum, in conjunction with wind and surface wave measurements will be instrumental in pinpointing specific wave generation and decay mechanisms.

c) To get the necessary array of measurements a Doppler sonar is being developed. Mounted on FLIP, the sonar transmits high frequency (80-90 kHz) sound in a very narrow beam. The sound scatters primarily off zooplankton. From the Doppler shift of the returning sound the relative velocity of the scatterers - and the water they are drifting in - can be determined. Preliminary tests of the concept using a borrowed sonar have produced velocity measurements out to a range of 800 m, with 20 m range resolution and 2 cm/sec rms velocity precision.

A difficulty with the concept is that the main beam of the sonar, approximately 1° wide, insonifies a relatively small volume of water, as compared to the volume insonified by the side lobes. In order that the dominant return echo result from the few scatterers in the central lobe rather than the many in the side lobes, it is vital that the sound level in the side lobes be very small.

d) A special purpose scattering sonar is being developed in 1978 which will have a beam pattern much improved from the borrowed prototype. Tests of the new sonar will be conducted during the summer of 1978, in preparation for a major data collection cruise during late 1979.

e) A power amplifier for the sonar has been developed which is approximately 90% efficient and can run continuously. As the anticipated duty cycle of the sonar is 5-10%, the power supply system developed for the first sonar can be used to run subsequent systems also. This results in a cost reduction of 30-50% in additional sonars.



Contour map of relative velocity (cm/sec) vs. range and time. Data taken from FLIP during January 1977 at 31°30'N, 122W. The sonar is mounted at a depth of 50 m on FLIP's hull slanting 7° down from horizontal. As a result increasing range (left scale) corresponds to increasing depth (right scale). The first 200 m of the beam in range show the turbulence in the lower mixed layer. Motion in the upper thermocline (greater range) is dominated by near inertial period waves.

World Ocean Circulation: South Argentine Basin, Weddell Sea and Atlantic-Indian Basin

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(b) The long-range objective is an understanding of the formation and circulation of the water masses of the world ocean. By this I mean a description of the major circulation system of the entire world ocean that includes the flow at all depths and is internally consistent in that it will account at least qualitatively for the distribution of both the conservative and the non-conservative characteristics at all levels as consequences of what we know of the surface exchanges of heat and water and of the wind-driven and thermohaline circulation.

(c) During the next year we propose to investigate the possibility that the deeper circulation within the Argentine Basin is part of the cyclonic gyre of the Weddell Sea. We shall measure the water characteristics in the southern Argentine Basin and between the South Sandwich Islands and the Mid-Atlantic Ridge, at about 55°S latitude. Current meters will be deployed in the Argentine Basin. Two or three short north-south lines across the southern part of the Argentine Basin, with current measurements, should identify the waters as to origin (Weddell Sea Deep Water or Weddell Sea Bottom Water) and allow some estimate of the intensity of the geostrophic shear and of the actual speeds. A line of stations from the South Sandwich Islands to the Mid-Atlantic Ridge should identify the characteristics of the waters along the western slope of the Mid-Atlantic Ridge and of the shear, and allow an estimate of the sense of flow of the abyssal waters there.

(d) We have arrayed the available hydrographic cast material for the Antarctic Ocean (defined for this study as the area south of 40°S) and prepared from this array maps of the characteristics of the deeper Antarctic waters and their flow. The work at sea in November-December 1978 will complete the maps in the area of the South Argentine Basin and allow the analysis to proceed.

(e) Results stemming from this grant within this year include a mid-depth circulation pattern in the North Atlantic and North Pacific oceans that is quite different from the pattern generally supposed. At 1000 m in the Atlantic (Reid, submitted) the Gulf Stream-North Atlantic Current is seen to extend eastward all across the Atlantic with a return flow westward just to the south of the Gulf Stream. Near 30°N 75°W this return flow turns southward and then eastward along about 25°N all across the Atlantic. The great wedge of saline water from the Mediterranean outflow is seen to extend westward with the return flow, from the Bay of Biscay to the Sargasso Sea. A similar pattern of flow is seen in the Pacific Ocean (Reid and Mantyla, submitted).

Other results include a study of the relation of the pattern of sound speed to the general circulation of the ocean (Reid, 1977) and a study of the characteristics of the abyssal water within the Marianas Trench (Mantyla and Reid, in press).

Salinity (‰) on the layer influenced by the outflow of the warm, saline, Mediterranean Water. The layer lies near 1000 meters depth near the Straits of Gibraltar but rises to less than 200 meters depth within the Norwegian Current.

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Long-range objectives

1. To achieve an understanding of the basic mechanisms which control the evolution of transient planetary and mesoscale phenomena in the sea.
2. To develop simple yet physically realistic models for simulating these phenomena in a quasi-deterministic and/or stochastic sense.

Present objectives

1. To investigate the dynamics of cyclonic and anticyclonic rings including spin-down, translation, topographic interaction, and ring-ring interaction, employing numerical modelling techniques.
2. To relate the results of parametric model studies to observed behavior of rings.
3. To investigate the spawning mechanism of rings from the parent current, employing modelling techniques.

Status of research

Studies completed or underway during the last two years include:

1. Frictionally-induced meridional circulation in an axially symmetric ring (M.S. thesis by P. Farrar).

2. Parametric study of the dependence of ring spin-down and translation speed on ring scale and ring intensity based upon a non-linear, two-layer numerical model with allowance for dispersive Rossby waves (a dissertation study by D. Smith still in progress).

3. Development of a depth parameterized numerical model to be employed in studies of the influence of topography on rings and in the stability of mean during currents (in progress).

a. <u>Western-Boundary Undercurrent</u>, Peter B. Rhines, Woods Hole Oceanographic Institution, Woods Hole, Mass. 02543, Tel. 548-1400, Ext. 547.

b. The long-range objective of the principal investigator is to help develop a consistent, modern picture of the dynamics of ocean circulation and of transient ocean currents. His methods involve theory, numerical simulation, and recently, ocean experiments.

c. This project is meant to be a thorough observational program describing the abyssal circulation along one segment of the western boundary of the N. Atlantic. Direct current measurements, as well as hydrographic, geochemical, optical, and radio-chemical signatures are being utilized.

d. The experiment is nearing completion. In May 78 the current meter array will be recovered, and the last of four hydrographic programs carried out. Theoretical work on a new mechanism of driving abyssal flow is complete.

e. Preliminary geochemical and hydrographic sections show clearly the far-northern origins of abyssal water, banked up against the Blake Outer Ridge at 30°N. Related theoretical work suggests that upper-ocean eddies, both nearby and far to the north and east, may be the prime motive force for this current (the classical description invokes, instead, the thermohaline circulation).

CYCLONIC GULF STREAM RINGS

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The long range objective is to measure features of the general ocean circulation in an attempt to describe and understand them. The principal focus has been on the transport and velocity structure of the Gulf Stream and deep Western Boundary Undercurrent (Richardson, 1977). A recent study consists of an investigation of Gulf Stream rings and their importance to the general circulation.

The objective of the Gulf Stream ring experiment is to describe the distribution, movement and decay of rings in the Sargasso Sea. The approach has been to use field experiments as well as historical data. One ring was followed for over a year by means of a variety of techniques and its decay rate established (Cheney and Richardson, 1976). An analysis of 50,000 temperature records obtained from NODC and Fleet Numerical Weather Central (1970-76) plus other sources was used to establish 25 ring time series plus 26 individual ring observations (Lai and Richardson, 1977). Approximately 11 cyclonic rings were found to exist at one time and they typically moved southwestward and coalesced with the Gulf Stream off Florida. During a four-month period in 1975 sufficient data were obtained so that we were able to make a quasi-synoptic map of the distribution of rings (ring census) in the western North Atlantic (Richardson, Cheney, and Worthington, submitted). South of the Stream we found nine cyclonic rings and north of the Stream, three anticyclonic rings.

During 1976-77 I participated in an interdisciplinary Gulf Stream ring experiment with several other investigators. We measured the time evolution of two cyclonic rings using satellite-tracked free-drifting buoys and a series of cruises. The movement of rings is complicated and appears to be related to the Gulf Stream, other rings and strong topographic features such as the Blake Escarpment, and Blake-Bahama Outer Ridge and the New England Sea Mount Chain. The usual fate of rings was to coalesce with the Gulf Stream and one of the following three things seemed to happen: 1) the ring turned into an open meander of the Stream and was lost, 2) the ring was advected rapidly (with speeds up to 75 cm/sec) downstream in the Stream and was presumably lost, 3) the ring became attached to the Gulf Stream and then split off again as a modified ring. Evidence suggests that a ring split into two pieces and that two separate rings collided.

Project Title: DYNAMICS OF OCEANIC MOTIONS

Principal Investigator: Professor Allan R. Robinson, Pierce Hall, Harvard University, Cambridge, Mass. 02138, (617) 495-2819

Overall Scientific Objectives: Research on dynamical and energetic processes in the sea; theory of ocean currents and general ocean circulation, of low frequency mesoscale phenomena (eddies) and interactions, mesoscale resolution numerical models including process and forecasting studies, design and analysis of field experiments.

Project Objectives: I. Theoretical studies of mesoscale low frequency variability of the open ocean of intense currents and the mid latitude general circulation including: studies related to the interpretation, intercomparison and verification of EGCM results; and the transient forcing of mid-ocean interior via both transient winds and Gulf Stream meander induced pressure fluctuations, II. Regional modelling of quasigeostrophic motions: with application to open ocean eddies including forecast experiments related to MODE and POLYMODE observations; and to intense current systems including mixed barotropic and baroclinic finite amplitude jet instability studies (related both to Gulf-Stream data and Gulf-Stream forecast experiments, and to the physical and oceanic interpretation of EGCM results), and III. Additional topics in process and regional dynamics.

Status and Accomplishments: I. Theory of Eddies, Currents and the General Ocean Circulation: A major numerical experiment (the first primitive equation, multi level, wind and thermally forced eddy resolving model calculation) has been completed and analyzed in depth, both kinematically and dynamically by novel methods for treating open regions of turbulent flow (Robinson et. al. 1977, Harrison and Robinson 1978). Studies of the i) parameterization of eddy effects on the mean, and ii) the analytical theory of the process of eddy energy propagation from the strong current generation region to the open ocean iii) ocean data/ dynamical scale analysis implications of the role of eddies in the general circulation, and iv) an overall review of EGCM modelling are (nearly) completed. G. Flierl (1977) has published his theory of Gulf Stream ring dynamics; P. Mueller will initiate analytical studies of eddy-eddy and eddy-mean field interaction. II. Regional Quasigeostrophic Modelling: A major study of the accuracy, stability and efficiency of three numerical models (finite difference, finite element and pseudospectral applied to open ocean test problems including frictional and filtering studies has been concluded and a Report widely distributed. Results indicate the feasibility of scientific application. A barotropic hincasting experiment, involving an open numerical model embedded in a larger numerical model forced with simulated MODE-I data and including boundary conditions and sensitivity studies is presently underway. III. Topics under study are mixed-layer coupling to quasigeostrophic motions and internal wave dissipation mechanisms.

OCEANIC FRONTS OF THE CENTRAL PACIFIC OCEAN

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The long range scientific objectives are the understanding of the frontogenetic and frontolytic processes in the ocean and the prediction of fronts. Prediction of the intensification and motion of fronts are important to the Navy, because (1) the thermohaline characteristics of the frontal zone are important for sound transmission; (2) frontal zones are often regions of minimum stability favorable for the development of turbulence; (3) storms often form and travel along oceanic frontal zones; and (4) fronts are regions of large velocity gradients.

The objective of the project are the understanding of the dynamics of fronts, both at the sea surface and at subsurface depths and of the atmospheric forcing of fronts. This includes numerical estimation of rates at which fronts intensify and weaken.

Research during the calendar years 1977-1978 dealt with the dynamics of the subarctic and subtropical fronts in the central Pacific. Several tasks were accomplished. The dynamics and structure of the subarctic front was successfully linked to atmospheric forcing (Roden, 1977). Rossby wave type perturbations of dynamic height, which are related to the appearance of regularly spaced subsurface fronts, were found to be common in the North Pacific; typical wavelengths are 400 km and the amplitudes decrease by a factor of three upon proceeding from the western to the eastern Pacific (Roden, 1977). A numerical model to predict the rates and patterns of frontogenesis expected from wind forcing was developed and tested in the subtropical Pacific. The model utilizes satellite sea surface temperatures and surface meteorological data as input (Roden and Paskausky, in press).

The Chapman Conference on Oceanic Fronts was convened by Roden and Mooers in New Orleans, La., 10 -14 October 1977. There were 175 participants, with many from abroad, to discuss the present state of knowledge on oceanic and atmospheric fronts, and future needs. The proceedings from this conference will be published in a special issue of the Journal of Geophysical Research.

FRONTAL DYNAMICS ON SEASONAL TIME SCALES
(Previous DYNAMICS OF SEASONAL VARIABILITY)

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Long range scientific objective of investigator. To develop the application of fundamental principles in fluid mechanics to specific problems in upper ocean dynamics which are relevant to climate problems, and to ecological as well as acoustical applications.

Project objectives. To develop the theoretical understanding of oceanic response to transient forcing which would allow a consistent dynamic diagnosis of the upper thermocline response to the seasonal time scale variations of wind stress and thermohaline forcing as observed,e.g. in GATE B and C scales, i.e. on scales of tens to hundreds of miles.

Current project status. While the objective of undertaking detailed diagnostics of GATE B-scale data has been frustrated up to now due to the state of the data base, several advances in analysis approaches have been made. The principal investigator is participating as invited speaker in a GATE workshop at Kiel, Germany, in May this year, on the basis of this work. Major effort in the current year is devoted to preparation for publication of earlier results. A two-dimensional density coordinate model for diagnostic and dynamic analysis of baroclinic frontal adjustment is being implemented as a PhD thesis project by a graduate student, Mr E Chien Foo.

Major accomplishments. The major accomplishment to date in this project has been to develop a consistent density coordinate based approach to the analysis of transient ocean dynamics. For the case of negligible interior friction, this allows the extension of earlier results in linear ocean dynamics to response amplitudes much greater in height displacement than the characteristic scale of stability variations. As an important byproduct, a powerful way of dealing with the influence of bottom friction and surface forcing on the steady and time dependent structures in a non-uniformly stratified ocean. Most intuitively striking is the already last year reported result that increasde bottom friction may in fact lead to decreased frictional damping of some planetary wave modes, along with a pronounced change in the modal structure for the vertical displacement of density surfaces.

1. (a) SOFAR FLOAT PROGRAM

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2. To study the kinematics and dynamics of oceanic motion on different length- and time scales.

3. To provide engineering, technical and communications support to the University of Rhode Island/Woods Hole Oceanographic Institution SOFAR float tracking program, the primary support of which comes from IDOE/NSF.

4. The redesign and implementation of the new SOFAR float signalling system and its concomitant technology has been completed and is now operational. We are presently installing micro-computer based signal processors and printers so that real-time float relocation and recovery operations can be expedited.

5. During the last two years of float experimentation we have made several significant observations. The first is that there is now rather solid evidence for eastward flow in the main thermocline between at least 24°N (floats) and 28°N (moored current meters). This appears to be in conflict with some of the classical hydrographic surveys of the western North Atlantic. Secondly, an anticyclonic eddy that was observed just off Grand Turk Island, was found to contain a significant amount of Mediterranean water. This was established through its T/S properties. It was later found to contain an excess of O_2 and Titrium, both of which suggest recent atmospheric exposure. Several papers of our recent research are either in preparation or have been submitted to various journals for publication.

OCEANIC VARIABILITY AND DYNAMICS

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The long-range scientific objective of my research is to understand better the properties of ocean currents and waves, particularly the vertical structure of the velocity and density fields. We are studying low-frequency, mid-ocean eddies, the influence of the ocean bottom on currents, and the generation of internal waves and microstructure. Our principal observational tool has been the electromagnetic velocity profiler (EMVP) developed under this project. A subsidiary long term goal is to exploit this technique to the point that it can have more widespread use.

The principal effort in 1977-1978 is devoted to the analysis and publication of observations collected in the multi-investigator study made in 1975 of fine- and microstructure in temperature and velocity and its relationship to larger-scale variability. We have found high levels of finestructure variability resulting from ocean eddies colliding with the island. Analyses of the microstructure observations are underway with Gregg and Gargett for the regions around Bermuda, in an open ocean mixed layer and within the Gulf Stream. A background, but active project is producing a summary atlas of all our velocity profiles as a first step toward a unified description of results.

The major accomplishments in 1977-1978 are:

1. An extensive description has been published by Hogg, Katz, and Sanford (1978) of the existence and spatial structure on entranced fine-scale variability (vertical scales larger than 1 m) generated around Bermuda.

2. A comprehensive description of the design and performance of our profiler has been published (Sanford, Drever, and Dunlap, 1978).

3. A new generation profiler, one which is expendable, has been designed and is now being tested. As of yet, acceptable performance for this probe is limited to the upper 100 m, but the present design should remove this restriction and allow operation to 750 m.

4. A paper has been published (Sanford, 1977) on transport measurements by electromagnetic induction on a narrow marsh drainage channel. Analysis continues on submarine cable data across the Florida Current.

Low-Frequency Large-Scale Ocean Circulation

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The principal aim of this project and of the principal investigator is to describe the properties of the low-frequency large-scale ocean circulation, with particular emphasis on the relation between eddies and mean flow.

Several exploratory long-term deployments of arrays of moored instruments in the North Atlantic have been completed in the past few years. Recent results have been published by Schmitz (1976a, 1976b, 1977, 1978) and McCartney, Worthington and Schmitz (1978). Continued analysis of the data base is in progress.

Major accomplishments are: (a) Eddy kinetic energy (K_E) levels have been shown to vary by orders of magnitude and to be related to the pattern of the general ocean circulation. Spatial coincidence of energetic eddies with the model equivalent Gulf Stream/Recirculation Regime is a basic property of eddy-resolving gyre scale numerical models. (b) The vertical distribution of K_E has been shown to be weakly depth dependent near the Gulf Stream along 55°W. In sharp contrast, the eddy field is essentially trapped to thermocline depths and above in the interior of the subtropical gyre. This type of dependence of vertical structure on energy level is one of the basic properties of local numerical models. (c) Spectral shape has also been found to be spatially inhomogeneous; with the largest contribution by the temporal mesoscale (periods less than 100 days) in the thermocline near the Gulf Stream and by longer time scales in the thermocline towards the interior of the subtropical gyre. Spectral shape is generally dominated by the temporal mesoscale at depths well below the thermocline. The normalized vertical structure for the temporal mesoscale (only) is remarkably geographically homogeneous.

Currents in the Charlie-Gibbs Fracture Zone (CGFZ)

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This project was an element of our continuing interest in the properties of abyssal flow and the nature of the influence of bottom topography on currents. Physical processes involved in the motion of deep water and its coupling to regions further up in the water column are inadequately observed and poorly understood.

Three moorings were set in CGFZ in 1975 as a pilot experiment to study vertical and horizontal variations in the properties of the mean and fluctuations in the vicinity of this opening in the Mid-Atlantic Ridge through which bottom water from the Norwegian Sea is known to be flowing. The moorings were recovered in 1976 after a nine-month exposure. This project was part of a cooperative investigation involving Marine Geologists, Chemists, and Physical Oceanographers at the Woods Hole Oceanographic Institution and the Scripps Institution of Oceanography. A manuscript on the mean flow and its Geological/Geochemical implications has been prepared by Shor, Hollister, Lonsdale and Spencer. A manuscript describing the characteristics of the low-frequency variability has been prepared by Schmitz and Hogg. We are also attempting to model the observations in terms of low frequency wave dynamics in a topographic regime simplified to retain the essentials of features of CGFZ and expect that this work will result in a manuscript in the near future. This particular project will end at the termination of present contract year, although as noted above, we have a continuing interest in abyssal flow.

The principal results of this investigation are: (a) A comparatively energetic deep eddy field was found, roughly twice as energetic as in the MODE-I area. The eddy field is two to six times as energetic as the mean field. (b) The vertical distribution of eddy kinetic energy was observed to be frequency dependent, increasing upward toward the thermocline for the longer time scales, and intensifying toward the bottom at shorter time scales.

Analysis of mid-ocean circulation

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Long-range scientific objective of principle investigator

Determine ocean mean and fluctuative currents in terms of model fits.

Objective of project

Applicability of beta spiral concept for mid-ocean circulation calculations.

Current status of the project

It has been shown(in cooperation with H. Stommel,M.I.T.) that it is possible to calculate absolute currents from stratification data alone, using the assumptions of geostrophy, linear vorticity conservation and density conservation.
By this method, absolute profiles of horizontal and vertical currents were calculated from hydrographic sections out of the North Atlantic, the South Atlantic and the Pacific.
The calculated downwelling velocity at the bottom of the Ekman layer in the central North Atlantic gyre fitted well with that calculated by other authors from the wind stress distribution.
In some areas there was a depth tendency observed in the results for the absolute currents at reference depth,the absosute currents came out smaller for deeper depth ranges of the stratification data than for shallow ranges.
At present different possibilities for that depth tendency are studied in order to implore the applicability of that method further.

Major accomplishment

A simple method has been devised to determine the components of mid-ocean circulation from available hydrographic data.

Currents at ocean boundaries

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Long-range scientific objective of principle investigator

Determine ocean mean and fluctuative currents in terms of model fits.

Objective of project

Determine the nature of low-frequency oscillations of boundary currents.

Current status of the project

Data from a moored array in an eastern boundary current, the Norwegian Current, had shown strong fluctuations of a few days period, and a subsequent analytical model calculation had suggested that the cause of these fluctuations might be baroclinic instability. At present the energy interaction terms between mean and fluctuative motions are being calculated from the measurements, and these calculations confirm the theoretical prediction.
A highly interesting but rather unknown western boundary current, the Somali Current, is being studied by moored current meter stations in a joint effort of R.S.M.A.S. and I.f.M. Kiel, Germany. The onset situation in the source region of the S.C., between 2^{o}S and 4^{o}S, was explored from measurements in 1976. These data also showed strong fluctuations in the period range of some days which remain to be studied.
In 1977/78 moored stations were out off Somalia, between 4^{o}N and 7^{o}N, to investigate the hypothesis that the S.C. might consist of two big eddies instead of a single current flowing along the coast.
The moored station work will be carried through to the international Somali Current experiment during FGGE in 1979.

Major accomplishment

Long-term recordings of Somali Current fluctuations.

The Dynamics of Cyclonic Gulf Stream Rings

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Long-range Scientific Objectives:

1. To increase our understanding of meso-scale phenomena by observations, analysis, and theoretical modeling
2. To assess the importance of meso-scale phenomena on the variability of the larger oceanic circulation

Project Objective:

To interpret cyclonic ring observations in terms of simple dynamical ideas so the evolution of the rings may be described.

Current Status:

Preliminary estimates of ring structure have been completed and a statistical data reduction scheme developed. Nine XBT star arrays have been obtained and comparisons of the rings at different times begun

Major Accomplishments:

1. Documentation of life cycle of a cyclonic ring by observing its trajectory, structure during its motion to the west and its final absorption by the Gulf Stream.

2. Development of quantitative techniques for comparing the ring at different times to assess the rates of change of energy and other properties.

TIME-DEPENDENT STRATIFIED FLOW OVER SLOPING BOTTOM TOPOGRAPHY NR-083-213

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The central task in this proposal is a description of the baroclinic motion induced by the barotropic surface tide in the vicinity of an island surrounded by a sloping shelf region. Are stratified edge waves, which propagate along closed depth contours, forced near resonance by the semi-diurnal tide?

In the original proposal, three coastal geometrics were to be considered—1) a straight coast 2) a straight channel 3) a circular island. Because the character of the trapped modes associated with these geometrics are so different, the work will focus on the island geometry, which is most relevant to the observations of Brooks.

Longuet-Higgins considered high frequency ($\omega > f$) wave motions around Macquarie Island using a barotropic model. He showed that no truely trapped modes exist around an island. The term trapped is usually associated with the exponential decay of the wave amplitude with distance from the coast. With circular geometry, the eigenfrequencies, are complex and energy leaks from the motion field near the island to the open ocean. Because the damping (in time) can be small for some modes, the waves are virtually trapped to the island. The "leakiness" of these modes allows an exchange of energy in both directions (into and away from the island), and provides a simple mechanism for directly exciting the free modes with an external energy source (the tides).

The high frequency, barotropic results of Longuet-Higgins are related to the two layer motions to be modelled.

For an island with circular geometry and unit radius, r=1, the shelf depth in the region around the island from r=1 to $r=r_0$, is given by

$$1 - h(r) = \Delta[(r-r_0)/(1-r_0)]^m, \quad 0 < \Delta < 1, \quad 0 \leq m < \infty .$$

By fixing Δ, the shelf depth at the island, and r_0 the shelf width, m can be varied continuously from the step-shelf mode (m=0) to the uniform depth mode ($m \to \infty$). The latter topographies can be treated analytically and will provide a starting point and accuracy check to the numerical calculations when m is arbitrary. The dependence of the wave amplitudes and the eigenfrequencies on (Δ, r_0, m) can be efficiently determined with this scheme. The resolution of the vertical distribution of energy is a principal goal of this analysis;

the effect of the bottom slope on the wave amplitudes forced by the tides in the bottom layer is expected to be substantial.

The preliminary analysis by Brooks on the transport data taken in the St. Lucia Passage shows the most intense fluctuations on the north side of the passage near Martinique. These results are consistent with the ideas that resonantly forced, stratified edge waves are propagating around Martinique, and not St. Lucia.

I expect to complete the calculations for the isolated island geometry this summer. With these results, a more complex model of the tidally induced currents in the passage between adjacent islands could be analyzed. The presence of another island may be significant since the wave trapping for these island geometries is imperfect (the "leakiness" of the free modes). Another aspect of the problem that is potentially important is the effect of coastal asymmetry. Weak asymmetries in coastal geometry, allow energy to be exchanged between the normal modes. Therefore, the resonantly forced stratified waves which propagate anticyclonically around a circular island may exchange energy with the weak cyclonicically propagating waves which are not directly forced at resonance.

A field study of the waves propagating around Martinique could be accomplished using three sensors (current meters or thermistors) located approximately 120^{o} apart around the island. Phase comparisons between sensors would allow one to determine the phase speeds of the propagating waves. Nelson Hogg of Woods Hole is using this approach to investigate the low frequency motion around Bermuda.

RADIO MEASUREMENTS OF THE SEA SURFACE

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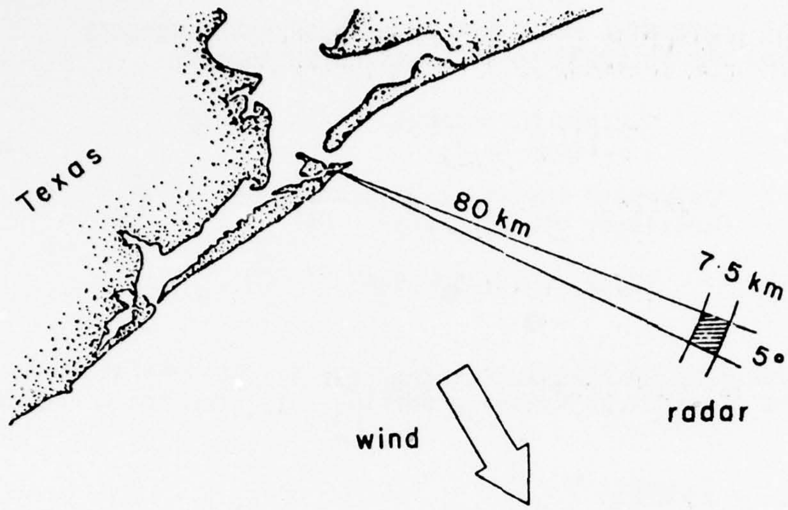
My long-range objective is to use radio waves of both centimeter and decameter wavelengths to observe oceanic variables difficult to measure by conventional techniques.

The decameter radio waves are resonantly scattered by typical ocean waves, and are used to measure precisely their amplitude, wavelength, velocity, and direction of travel. Working with colleagues at Stanford University, we have used scattered LORAN-A signals recorded at Galveston Island to measure the growth and decay of 7-second ocean waves. We find that the rate of wave growth varies as the cosine of the angle to the wind, and that wave decay is much weaker than wave growth. When the wind suddenly reverses, as following passage of a front, growth of new waves going with the wind must wait for the old waves to die down.

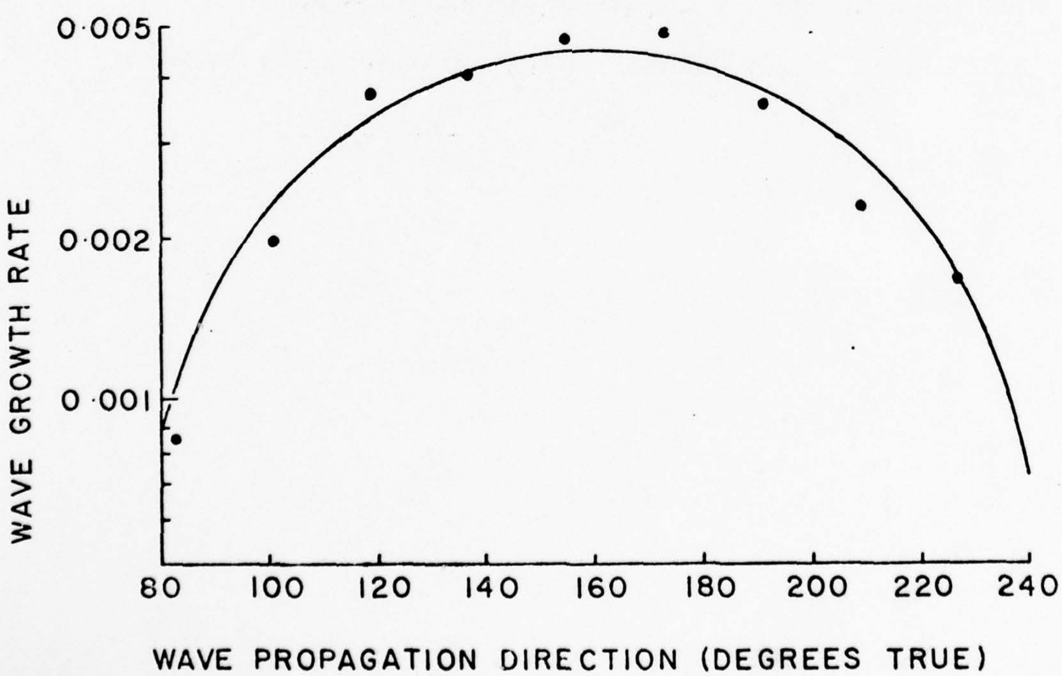
In another joint experiment with Stanford, this one at Pescadero California this January, we used decameter signals to measure ocean surface currents and the ocean wave directional spectrum during varied wind and wave conditions. At the same time the current was also measured by drifting buoys, and the wave spectrum was observed with a pitch-roll buoy. By comparing these measurements we expect to determine the ability of the radar to measure the directional spectrum of waves, to calculate the relative importance of wind and waves in producing surface currents, and to determine the ability of the radar to measure weak surface currents. Similar but more comprehensive experiments will be done this summer as part of the large international experiment JASIN in the Atlantic off the coast of Scotland.

Centimeter wavelength radio measurements form the basis of a new satellite for observing the oceans, SEASAT-A, due to be launched in May 1978. To evaluate the status of these radio measurements, I helped organize a Colloquium on Radio Oceanography held at Hamburg in October 1976, and edited the papers presented there. These will be published in a special issue of Boundary Layer Meteorology.

This summer I expect to participate in two experiments to characterize the performance of the satellite instruments with the eventual goal of using the satellite to study the sea. The first will estimate the ability of the Synthetic-Aperture Radar to image ocean waves by comparing spectra calculated from the images produced by the radar with wave specra measured by wave buoys. The second will estimate the ability of the Scanning Multifrequency Microwave Radiometer to measure rainfall by comparing rainfall estimates from airborne instruments with rainfall calculated from the satellite observations. Both experiments will be part of the much larger JASIN Experiment.



GALVESTON ISLAND EXPERIMENT



Galveston Island Experiment. (above) Typical angular and spatial resolution, drawn to scale, of radar observations of wave growth. (below) Fractional rate of wave growth per period of 7-second waves under the influence of 10 m/s winds from the northwest, 340°T. The smooth curve, 0.0044 cosine (degrees true -159°), is the least-squares fit of a cosine to the data.

MAPPING THE HORIZONTAL STRUCTURE OF NEAR-SURFACE CURRENTS DURING THE POLYMODE LOCAL DYNAMICS EXPERIMENT

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Long Range Objectives of Principal Investigator: An understanding of the dominant physical processes governing the large scale oceanic circulation.

Objectives of the Project:

1. Compare the horizontal structure of near surface (shallower than 100m) and deep velocity fields of a mesoscale eddy.

2. Examine the degree to which structure of the surface layer and deep eddy are coherent.

3. Obtain a basic data set to aid the design of experiments to study the dynamics of eddy-surface layer interactions.

Current Status of the Project: Preparing to go to sea in May of 1978.

Studies of Ocean Circulation

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The long range objectives of this work are to understand several features of ocean circulation as they are evidenced by analysis of observations. The objective of this project is to understand the time-dependent circulation in the Gulf of Mexico; this small but conveniently-located ocean seems to exhibit a time-varying western boundary current and has a Sverdrup-like interior driven by the curl of the wind stress. The program has been made more interesting by the presence of large rings (pinched off from the Loop Current) which seem to be analogous to those in the Gulf Stream system. Mr. Blaha has found clear variations in the baroclinic signal across this current after it has left the coast. The minimum baroclinic signal is in October (± 1 month). The fluctuations seem to be coherent with the large-scale wind-curl forcing. With Mr. Brady Elliott (of Texas A&M) we are comparing two available wind data sets; a time series, computed from a 3° grid of surface pressure (by Bakun) and mean monthly winds, on a 1° grid, from ship observations.

The most attractive hypothesis for explaining the Gulf circulation (away from the Loop Current) is that the observed response at periods of 6 months is in part a barotropic response, which advects the baroclinic field past a fixed point.

Mr. Horton has been working with a theory of buoyant forcing for steady currents, in which there is mixing across density surfaces. The mixing of course is small but the release of energy involved, in the steady flow, is dynamically important. A manuscript on this subject has been submitted to Journal of Marine Research. We are continuing to work on a better understanding of several of the assumptions involved.

FEASIBILITY STUDY FOR IMPROVING THE AN/SSQ-36, THE NAVY'S AIRBORNE EXPENDABLE BATHYTHERMOGRAPH (AXBT)

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A cooperative program is underway to study the feasibility of improving the current Navy AXBT, specifically by replacing the thermal sensor in this unit with the Sippican T-7 ship XBT. (The AXBT is an aircraft-launched expendable. After hitting the water, an antenna deploys and a telemetry transmitter is activated. A thermal sensor, connected by wire-link to the telemetry set in the floating body, is then released and obtains a temperature profile that is transmitted to the aircraft. Given a known drop rate, the temperature-versus-time data can be converted to temperature-versus-depth.)

A comparison of the specifications for both the current and the improved AXBT's is as follows:

	Current	Improved
Temperature accuracy (deg C, rms)	0.55	0.2
Depth range (m)	305	800
Drop rate accuracy (%, rms)	5	2
Time to obtain temperature profile (sec)	200	129

Sippican has developed a self-calibrating electronic interface which couples the T-7 XBT with the telemetry set in the buoy, and has conducted temperature and shock tests on the T-7 probe. These tests are necessitated by the low environmental temperatures and high thermal and physical shocks associated with high altitude launch conditions. The new electronic interface calibrates itself, measures the thermistor resistance, and feeds the appropriate signal to the transmitter: the breadboard circuit has passed initial tests. Production quantity pricing of an integrated circuit interface, and production unit cost estimates are being studied for possible cost/benefit tradeoffs.

NADC provides design-constraint data and testing for P-3 flight/deployment conditions, while NRL is responsible for system accuracy testing.

The ultimate objective of this program is to make available to the scientific community and the Navy a synoptic thermal measurement capability, in which the capability of the T-7 ship XBT for making accurate thermal measurements is mated with the capability of the Navy P-3 aircraft for rapid coverage of relatively large oceanic areas.

KUROSHIO TRACKING EXPERIMENT

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LONG RANGE SCIENTIFIC OBJECTIVES The project goal is to produce an understanding of mesoscale features associated with strong current regimes. The research area encompasses the description and analyses of oceanic movement and development of mesoscale perturbations to mean conditions.

PROJECT OBJECTIVES The tracking experiment goal is the description of motion in the North Pacific Ocean including the Kuroshio and Kuroshio Extension Currents. Analyses of drifter trajectories relate the motion to physical, biological and meteorological distributions. Emphasis has been placed on interactions between the Kuroshio Extension Current and the Emperor Seamount Chain.

CURRENT PROJECT STATUS The project has received telemetered data from 4 satellite-reporting drifters launched in February 1977. As of March 1978, two drifters remain reporting regularly north of the Hawaiian Islands, another is intermittent and one has grounded off Samar Island, Phillipines. Work status: comparison of trajectories with mean temperature, density and dynamic topography fields (90%)*; comparison with NORPAX XBT data, GOSSTCOMP sea surface temperature analyses, Japanese 10 day reports (70%); spectrum analyses of velocity components and temperature records (50%); coherence analyses between drifter data and meteorological parameters at Emperor Seamount Chain (10%); comparison with biological distributions (50%).

MAJOR ACCOMPLISHMENTS The drifter trajectories reveal a remarkable diversity from close launching athwart the Kuroshio current; the drifters can be widely separated and return to close proximity; the effects of mesoscale eddy generation were detected to the north and south of the Current; flow in the Kuroshio Countercurrent was traced as well as flow into the Oyashio Frontal Zone; Current interaction at the Emperor Seamount Chain was revealed in three instances; eddy presence east of the Chain was detected and verification of the diffusing effect of the topography obtained; estimates have been made of zooplankton exportation and a lower limit on life expectancy on the basis of one trajectory north of the Current. A paper: "Biological Implications of Long Term Drifter Trajectories in the North Pacific", Hagan, Vastano, Kirwan, McNally, Bieri, has been submitted to Science. Two notes have been published on the drifter experiment in Naval Research Reviews and the ONR Tokyo Scientific Bulletin.

* Percent completion

CYCLONIC RING EXPERIMENT

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LONG RANGE SCIENTIFIC OBJECTIVES The project goal is to produce an understanding of mesoscale features associated with strong current regimes. The research areas of interest are the description and analysis of cyclonic ring physical characteristics.

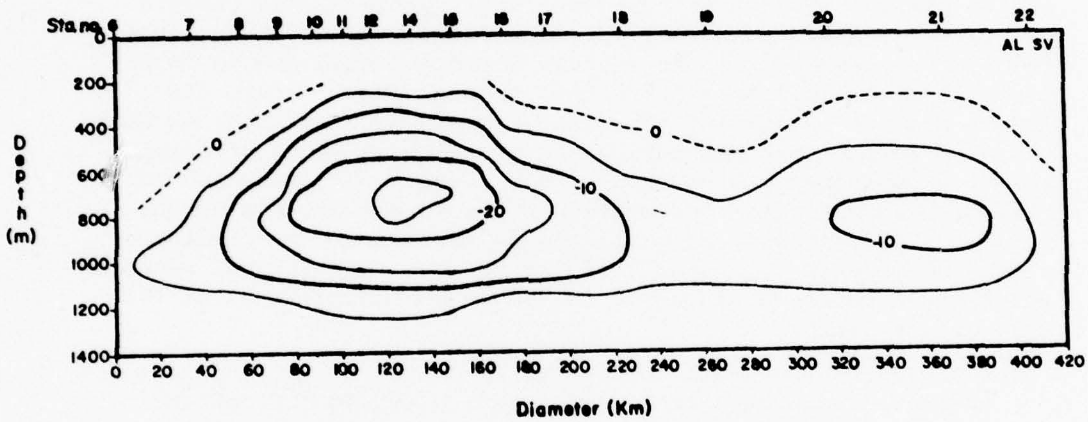
PROJECT OBJECTIVES The field experiment goals are the acquisition of physical data, hydrographic station and XBT processing, preparation of station and XBT sections, physical data report preparation and dissemination. Analyses include comparison of ring structures and energy distributions, entrainment and diffusion, transformation of water masses, volumetric water mass census, preparation of initial and verification data for numerical models and climatology of the North American Slope Water (NASW). Guidance for the Experiment is provided through membership in the Ring Steering Committee.

CURRENT PROJECT STATUS The project has received CTD station data for 3 of 4 primary ring cruises, XBT data for all primary ring cruises and XBT data from 4 cruises of opportunity; 89 hydrographic stations have been processed, 2076 XBTs digitized and archived on tape, 9 hydrographic and 42 XBT sections drawn; Data Report (DR) I (KNORR #62) published, DR II (KNORR # 65) (75%)*, DR III (ENDEAVOR#11) (75%), DR IV (KNORR#71) (25%), DR V (Ships of Opportunity) (50%). Work status: geostrophic velocity computations (75%); sections preparation (40%); volumetric water mass census (20%); physical property and energy anomalies for 1967 ring, Big Baby A (100%), 1977 rings (15%); entrainment and diffusion by density distributions for 1967 ring (100%), 1977 rings (0%); transformation of tropospheric waters for 1967 ring (100%), 1977 rings (15%); motion of Lagrangian water parcels in cyclonic rings using 1967 ring data (80%); error in XBT section analyses due to ring shape and motion for different sampling strategies (30%); areal distributions of water masses, distribution statistics, regression analyses on distribution parameters in NASW for 1976-1977 (80%); preparation of initial conditions for N-level ring model based on 1977 ring data (40%).

MAJOR ACCOMPLISHMENTS (1) participation on all 4 primary ring cruises by project personnel, (2) paper: "Comparison of Cyclonic Ring Structures" given at Chapman Conference on Oceanic Fronts; (3) detection of possible water mass modifications during ring evolution; (4) comparison of physical property anomalies for cyclonic rings and big baby rings near Bermuda indicates similar strengths; two papers published: "Decay of a Shoaling Gulf Stream Cyclonic Ring", Schmitz and Vastano, J. Phys. Ocn. V7, N3, May 1977; "Observational Evidence for Transformation of Tropospheric Waters within Cyclonic Rings", Vastano and Hagan, J. Phys. Ocn. V7, N6, Nov 1977; one paper submitted to J. Phys. Ocn., Feb 1978, "A Comparison of Cyclonic Ring Structures in the Northern Sargasso Sea", Hagan, Olson, Schmitz and Vastano.

* percentage completion

CYCLONIC RING EXPERIMENT



Sound velocity anomaly (m/sec) relative to Sargasso Sea background for Ring Al of the Cyclonic Ring Experiment.

OCEANIC FRONTS

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A long-term objective of the principal investigator is to understand and describe those processes in the upper ocean which are responsible for the observed variability of its currents and physical properties, and which control the energy exchange with the deeper ocean layers and with the atmosphere. The objective of the present project is to investigate by field measurements the cause of surface and near-surface frontogenesis in the subtropical convergence of the western North Atlantic and to establish, if possible, the relationship between these fronts and deeper mesoscale motions. The measurements were carried out from the NOAA ship RESEARCHER during the first three weeks of March, 1977. A paper describing some of our results was presented at the Chapman Conference on Oceanic Fronts in New Orleans during October, 1977 and will be published in the summary proceedings of the conference this year (with A. Leetmaa as principal author, see list of refereed papers). The major accomplishments of this work are as follows:

1) Surface frontogenesis appears to be driven by the currents of small scale baroclinic eddies which act to concentrate lateral density gradients and, through small vertical motions, convert near-surface potential energy to the high levels of kinetic energy observed along the fronts (currents of 80 cm/sec). The small eddies are observed to have a horizontal scale of about 100 km (wavelength), a time scale of about a week, and a depth scale of about 300 meters. Their origin is unknown at present but we speculate that it comes from the mesoscale motions (wavelength $\simeq$300 km).

2) The time scale of the frontogenic process appears to be of the order of 1 to 4 days, with a cross-frontal scale of 10 km, and an along frontal scale of 100 km.

3) Frontogenesis appears to be irreversible, that is, they extract energy from the small eddies but do not give it back. It is not clear where this energy goes.

LARGE-SCALE CIRCULATION

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Long-range scientific objectives: To explore and interpret features of the large-scale ocean circulation and associated distribution of properties; including the pattern and rates of deep circulation in the world ocean, the structure, behavior, and dynamics of the major ocean currents, and effects of bottom topography on oceanic flow.
Present project objectives: Present objectives concern (1) mapping and interpreting features of the Gulf Stream; (2) delineating the overall deep circulation of the Indian Ocean; and (3) investigating the dynamics of deep western boundary currents.
Current status: During the calendar years 1977-78, the results of a three-ship investigation of the Gulf Stream and associated currents southeast of the Grand Banks of Newfoundland, carried out in 1972, were written up for publication, in collaboration with colleagues at the Bedford Institute of Oceanography. Editing and reduction of data taken on a transindian hydrographic section along Lat. 18°S in 1976 were completed; study of that material and preparation of profiles illustrating the property distributions was begun. Analysis of a short section occupied in the southwestern Madagascar Basin during the same cruise proved that the deep boundary current off Madagascar is supplied from the Crozet Basin, rather than the Mozambique Basin to the west. Some time was spent trying to understand effects of bottom slope on stratified deep boundary currents, but the mathematics is difficult, and no substantial progress was made.
Major accomplishments: Geostrophic interpretations of the data taken during the Grand Banks survey--the most detailed and extensive ever made in that area--indicate a Gulf Stream-Slope Water Current system which splits into two branches over the Southeast Newfoundland Ridge, with a subsidiary closed circulation in the Newfoundland Basin. With a plausible degree of lateral mixing, this current system has been shown consistent with the distributions of other properties in the region (salinity, dissolved oxygen and silica), and it has thereby been shown unnecessary to rationalize them by hypothesizing, as Worthington did, two separate nongeostrophic gyres, in violation of basic physics.

Closely spaced hydrographic stations made along Lat. 18°S in the Indian Ocean demonstrated the existence of a deep western boundary current in the eastern Indian Ocean, flowing northward beside the Ninetyeast Ridge. It had been inferred from coarse, large-scale property distributions and dynamical arguments that such a current "ought" to be there, and it was gratifying to find that indeed it was. Knowledge of its existence helps to explain certain features of large-scale property fields (*e.g.* the deep oxygen distribution), as well as provide further confirmation for deep-circulation theory.

Transfer of Energy Among Modes
Within the Oceanic Internal Wave Field

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Professor Kenneth Watson has a continuing interest in studying the statistical mechanical properties of dynamical systems. This includes aspects of turbulence and transport phenomena in fluids.

The present project is directed toward the study of internal wave related turbulence in the ocean. Specific objectives are to understand the mechanism of energy transport within the internal wave field and related diffusion phenomena.

The project was initiated in early December, 1977. The nonlinear interaction of internal waves has been expressed in dynamical form in terms of Hamilton's equations. These have a form which can be conveniently integrated numerically and also lend themselves to analytic approximation.

The decay of a single labelled internal wave mode interacting with an ambient field has been studied and has been related to a vertical diffusion coefficient.

Studies of the Oceanic Bottom Boundary Layer

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The long-range scientific objective is to gain insight into the physical processes which determine the structure and variability of the oceanic bottom boundary layer in regions of energetic flow. The objective of the project in this contract year is to numerically model the benthic boundary layer in regions of sloping bottom topography to assess the effects of horizontal advection and tidal forcing in determining the structure and variability of this boundary layer. At present we have a model which permits tidal forcing effects to be included and we are in the process of modifying it to realistically simulate the effects introduced by a sloping bottom. The model indicates that for the region in which we have actual data the presence of a sloping bottom significantly modifies the structure of the boundary layer.

Project

Development of a towed, two component surface current sensor.

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Long range scientific objectives of PIs

Investigation of mesoscale dynamics of Eastern N. Atlantic

Development of oceanographic instrumentation.

Project objective

The project aims to build a near surface towed body incorporating two velocity component, heading and temperature sensors the outputs of which when processed in the deck control unit and combined with satellite navigation information will yield values of near surface currents over the periods between satellite positions.

Current status

The project is a joint development between the UK Institute of Oceanographic Sciences and the Woods Hole Oceanographic Institution. The electronics package for the towed fish has been constructed and incorporates sensors for the determination of the stability of the towed body during the initial trials. This work has been done by Mr. D. Bitterman of WHOI who is now working at IOS. The design of the towed fish body has been completed and construction will start shortly. Initial trials are scheduled to take place on the R/V Gyre during the POLYMODE Local Dynamics Experiment in which an intercomparison with the hull mounted acoustic backscatter system will be possible. If this schedule cannot be met we will carry out trials on the RRS Shackleton in July (intercomparison with a 2-component, hull-mounted log) or the R/V Atlantis II during and after the JASIN experiment.

TITLE: Study of the dynamics of large-scale thermal variability in the upper waters of the mid-latitude North Pacific.

PRINCIPAL INVESTIGATORS:

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The object of this study has been to gain understanding on the physical mechanisms responsible for the large-scale seasonal and secular changes in the thermal structure of the mid-latitude North Pacific. This study is one component of a joint multi-university program (i.e., the Anomaly Dynamics Study) designed to test various hypotheses concerning the large-scale baroclinic response of the ocean to transient winds. This last year was an exciting time of the Anomaly Dynamics Study (ADS) and for ourselves in particular. We observed an autumn/winter anomaly event in the Westerly Wind system that had surface wind stresses that were 3 standard deviations above normal for a period of 2-3 months. The surface current response to this, as measured from satellite-tracked surface drifters (drogued at 30 m) was a surface current drift of 20 cm/sec, moving at 40° to the right of the wind, in quasi-agreement with Ekman flow computations. This means that the physical mechanism of Ekman pumping in response to the wind stress curl, should have been operating to alter the vertical position of the main thermocline. However, this was not observed. Rather, evidence of vertical mixing down to 400 m was found. Directly underneath the anomalously high winds the temperature in the mixed layer (in the upper 150 m) were 3 standard deviations colder than normal; below that in the main thermocline the temperatures were 3 standard deviations warmer than normal. This is the opposite response expected from Ekman pumping theory, but is in agreement with the concept of vertical mixing, which has the signature of reducing the vertical temperature stratification by cooling the region above the main thermocline and warming it below.

In the ensuing spring and summer months, after the 1976-77 autumn/winter anomalous forcing event, the temperatures in the main thermocline began to become colder than normal, suggestive of vertical diffusion downward of the anomalously cold water found at the surface during the previous autumn/winter. However, investigations from hydrographic data taken before and after the 1976-77 autumn/winter period (ADS I cruise in

June 1976 and ADS III cruise in June 1977) indicate that this cooling in the main thermocline may have come from horizontal advection by geostrophic flow along isopycnal surfaces, associated with a reduction in the salinity.

These results from hydrographic cruises emphasize the importance of gathering salinity data as well as temperature data. Therefore, the next year it is important for the ADS program to investigate seriously the possibility of gathering salinity information from a deployment of the XSTD, in the same way that temperature information is now being gathered by XBTs placed on board ships-of-opportunity. This kind of measurement is indicative of a departure from previous objectives, which were to investigate the dynamical influence of the wind stress upon the thermal structure; in the future thermohaline processes and mixing processes will have to be studied.

Salt Fingers and Microstructure

Vertical mixing in the ocean interior occurs by a combination of advection, mechanical stirring, and diffusion. Diffusion, which is ultimately responsible mixing, is the principal process in certain low shear ocean regions. Salt finger convection (warm, salty fluid in sinking cells exchanging heat with cool, fresh fluid in rising cells) appears to be the dominant process in staircase structure in the tropic and temperate oceans. In more active regions, shear flow turublence appears to dominate. I wish to understand the relative importance of these processes in vertical mixing in various oceanic cases.

In this project, an instrument ensemble which sinks freely, recording temperature, conductivity, and pressure, while photographing shadowgraph images of index of refraction inhomogeneities, has been deployed in staircase structure and high shear structure. The objective has been to categorize mixing processes by the alignment of the structures made visible in the shadowgraphs. A velocity shear sensor added to the instrument now allows shear to be observed at interfaces to determine thresholds for salt finger convection (which should occur nearly everywhere in the Atlantic without some inhibiting process). The determination of these conditions is the present objective of this project.

The year 1977 has been a period of analysis. This is continuing in 1978, principally on data from the Gulf Stream and a cold core Gulf Stream Ring.

Electronic instrumentation to record conductivity, temperature, and depth was constructed in 1975 and housed in an autonomous, sinking vehicle. Profiles were made in support of the AFAR Microstructure Program of March 1975 in the Azores with this equipment. An optical imaging system to identify microscale stirring structures and an acoustic velocity shear sensor were added to the instrument for participation in the October 1975 FAME cruise to the Bermuda area. On this cruise, mixed layers 15 meters thick were observed to contain velocity structure through the layer and shear at the layer interfaces. Interfaces of warm, salty water overlying cool, fresh water did not commonly exhibit salt fingers as had been previously observed in the Mediterranean Outflow. Thus velocity shear apppears to dominate double-diffusive convection in the regions analyzed, the opposite case from the Mediterranean Outflow.

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Velocity Structure of Boundary Layer Flows

Deep sea boundary layer flows are an important cause of sediment erosion, transport, and deposition. The interaction of flow and bedform is difficult to simulate in the laboratory yet the shear stress on the sediment depends on the structure of the turbulent flow imposed by the bedforms. I would like to describe the stresses in the flow and understand the flow-bedform interaction in a variety of benthic flows.

The objective of the present project is to develop deep sea velocity sensors and deploy them in a high energy flow such as the Western Boundary Undercurrent for instrument evaluation and preliminary observations of the flow stress near the bottom.

An acoustic current meter has been developed as a three-axis, four-sensor array for deep sea turbulent flow measurements. It has been tested in a shallow tidal flow from which current profiles and Reynolds stress profiles were obtained. A second instrument is being prepared for deployment in an active deep site.

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The Relation of Sediment Movement to the Benthic Current Flow in the Florida Straits

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Long-Range Objectives. To develop as full an understanding as possible of: (1) the hydrodynamics of the frictional boundary layer at the bottom of the ocean; (2) the interaction of this layer with the sea-bed, in particular the relationship of hydrodynamic parameters to sediment transport and resulting bed forms.

Objectives of Current Project. The project is designed to investigate the relation between movement of sediment ripples and overlying current flow at a high energy deep-sea site.

The field program has three components:

(1) A site survey to locate a uniform region of bottom sediment with well developed bedforms of less than one meter scale.

(2) The nearby installation of a specially designed apparatus (see figure) containing on a fixed tripod frame:

- (a) vector-averaging current meter (VACM), recording the current velocity at an elevation of 1 meter
- (b) stereo 16 mm camera pair to take time lapse motion pictures of the migrating sediment ripples in a 1x1.5m area
- (c) strobe light to illuminate the bottom
- (d) acoustic release system for recovery of the apparatus.

Above the tripod and attached to it will be a string of four VACMs at elevations of 3, 10, 20, 60m. Several times every hour, for a period of a month, this apparatus will record the average current velocity vector and take a stereo color photograph of the sea bed.

(3) Obtaining relatively undisturbed samples of the sea bed in the vicinity of the apparatus.

In the analysis, data from these components will be brought together to relate the observed changing bed-form to the sediment composition and the overlying flow. It is hoped that this will result in a significant increase in understanding of the interaction of current and bottom sediment in the deep-sea environment.

Current Status. A newly designed tripod frame is being built to improve the reliability of the release system mechanism. The apparatus will be deployed in June either on the lower continental rise in the Western Boundary Undercurrent or on the Bermuda Rise in the Gulf Stream Return Flow. For a period of 3-4 months the cameras will take one stereophotograph per hour, while the current meters record (8 times per hour) the boundary layer velocity and temperature profiles.

Accomplishments. A 6-week time lapse motion picture film of the sea bed at 710 meters depth was obtained in the Florida Straits during the summer of '76. Simultaneously,current was recorded at various levels in and above the benthic boundary layer. Sediment was observed to be moving during 17% of the record, and optimum predictive criteria for bed-and suspended-load transports were developed, based on the current records. Bottom samples from the region were obtained with ALVIN for laboratory analysis. Initiation of in situ sediment motion was found to occur at flow speeds half as great as those required in idealized laboratory flows with similar sediments.

WATER MASS FORMATION AND GULF STREAM VARIATIONS

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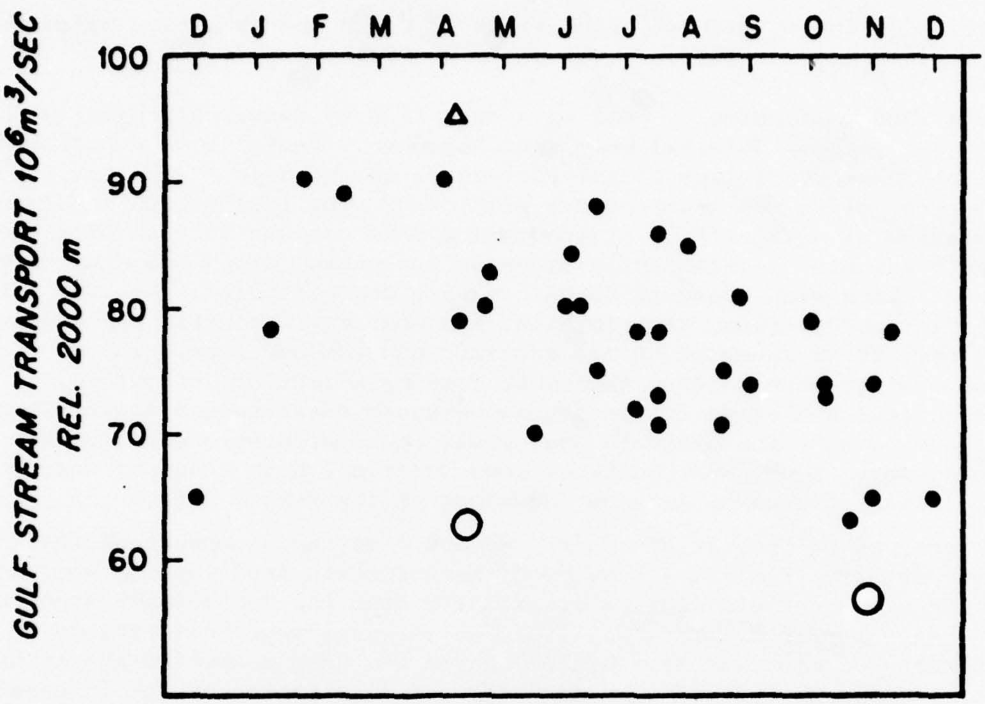
My scientific aim is to study the water masses of the world ocean and their formation. In particular, I intend to focus on the deep mixed layers of 18°C water that are formed immediately offshore of the Gulf Stream in late winter. I have hypothesised that the formation of these deep mixed layers brings about a deepening of the main thermocline south of the Stream and that, as a result, the Stream increases in volume transport at the end of each winter.

The main objective of the project is to test this hypothesis. The attached figure shows the computed volume transport for 32 reliable oceanographic sections across the Gulf Stream in a region between North Carolina, Nova Scotia and Bermuda. The Stream appears to be strongest in late winter after the deep mixed layers are formed and weakest in late fall, consistent with this hypothesis. There is also evidence (from only two sections) that the Gulf Stream was weakest after a succession of mild winters (open circles), and strongest (from only one section) after a severe winter such as that of 1976-1977 (open triangle). Deep mixed layers are also found on the equatorward side of other major ocean currents such as the Kuroshio, the Somali Current and the Antarctic Circumpolar Current; the hypothesis may also apply to these currents. Existing data are insufficient either to confirm or refute the hypothesis, and the exact mechanism by which the thermocline is deepened (if indeed it is) is not at all clear.

The project has been halted for the current year until previous contract work can be completed and published. It is hoped that a modest start can be made in 1979 by means of oceanographic sections across the Gulf Stream on a "piggy-back" basis, and by examining the effect of past winters on the depth of the mixed layer and the thermocline in historical data.

The major accomplishments of this project are the published papers listed in the bibliography.



Computed geostrophic volume transports for sections in the Bermuda - Nova Scotia - Cape Hatteras triangle: •, 32 sections made between 1932 and 1968; O, sections made before and after the winter 1974-75; Δ, between Researcher stations 6 and 33 in April 1977. All transports are relative to 2,000 m and are plotted against month.

Internal Waves, Equatorial Dynamics and Acoustic Tomography

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Long range objectives. This is a many faceted research project with several goals. Internal wave work has been directed to an understanding of the characteristics of internal waves in the deep ocean, their sources, sinks and interactions with other flow fields, and topography. Dynamics of equatorially trapped baroclinic motions (a form of internal wave) capable of efficiently transporting energy along the equator and interacting with boundary flows are also to be studied. We seek their energy, energy flux, distribution, and sources. Acoustic tomography is new; it is intended to use acoustic sources and receivers in conjunction with inverse theory to form an efficient, effective, economical real-time system for large scale measurements and monitoring of the ocean. The ultimate goal would be to produce ocean acoustic holograms. A new near-surface, long-duration, high accuracy current profiling instrument is under development for future use.

Objectives of present contract. We are studying 3 aspects of the internal wave field. A summary of measurements from regions where the internal wave field departs drastically from the "universal" spectrum is being prepared. This will form an internal wave "climatology". An array of moorings from Hudson Canyon has been recovered and is being studied for the trapping, breakdown, and dissipation of the internal wave field at very high energies in a location where the field can have geological effects. Characteristics of the inertial motions in the deep ocean are being measured to understand their kinematic character and origin. In the equatorial program, we are obtaining measurements from moored instruments in the Gilbert Islands to determine if the deep time dependent motions there are consistent with recent theories. Previous data from the equatorial Indian Ocean is being analyzed. The acoustic tomography work is intended to understand the theoretical limits to acoustic measurements, and the optimum strategy for performing the inversions for ocean structure.

Current status. We are in the middle of the first deployment of the Gilbert Island array. The Hudson Canyon array data return was 100% and preliminary analysis is underway. CTD data is being edited at WHOI for our use. A manuscript describing the acoustic tomography technique has been completed.

Major accomplishment. Perhaps the most important conclusion is that the acoustic tomography idea should work. It could have a revolutionary impact on oceanography.

SECTION VI---BIBLIOGRAPHY

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This report presents a summary of work sponsored by the Physical Oceanography Program (Code 481), Ocean Science & Technology Division, Office of Naval Research, covering the FY 77-78 period. It includes a brief description of (1) the status of research for each of eleven different areas of physical oceanography, (2) each of the seven multi-investigator, multi-institutional, and multidisciplinary projects which ONR 481 jointly sponsors; (3) each of the 99 individual projects which ONR 481 sponsors, and (4) all refereed journal articles appearing during 1976-78. (Cont on p I-1)

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