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# NEEDS, OPPORTUNITIES AND STRATEGIES FOR A LONG-TERM OCEANIC SCIENCES SATELLITE PROGRAM

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*A Report to*
*The National Aeronautics and Space Administration*
*(NASA)*
*by the*
*National Oceanographic Satellite System (NOSS)*
*Science Working Group*

NASA/NOSS Science Working Group

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*Frontispiece:* Two intense atmospheric disturbances apparently join forces. What are the dynamics that produces these visible manifestations? Are they really connected? Twenty years of satellite remote sensing have produced a vast data base of day and night images at high resolution in many portions of the electromagnetic spectrum. Their use in meteorology is indispensable.

Analogous observations of the oceans are nascent—proofs-of-concept have been completed. Where do we go from here? This report attempts to discuss some of the possibilities and provides some guidelines for future efforts.

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# PREFACE

During the later part of the previous decade, the National Aeronautics and Space Administration (NASA), together with the National Oceanic and Atmospheric Administration (NOAA) and the Department of Defense (DoD), planned for the first operational demonstration of a spaceborne ocean observing system, the National Oceanic Satellite System (NOSS). As then conceived, the first NOSS satellite was to have been launched in 1986. This system would have been based on the heritage and successful proof-of-concept demonstrations afforded by Skylab, GEOS 3, Nimbus 7, and Seasat.

As a means for addressing the scientific needs of the oceanographic community as a whole, the NOSS Science Working Group was formed in the spring of 1980 under the chairmanship and guidance of Dr. Francis P. Bretherton. The Group was charged with three tasks: first, to recommend sensor modifications and additions to fill the 25% of the spacecraft capacity which had been reserved for research purposes; second, to identify research problems amenable to solution utilizing NOSS data; and third, to recommend appropriate facilities for the research community to use NOSS data effectively in the solution of these problems. This document conveys their recommendations.

Since the formation of this group, the ground rules have been changed: NOSS was deleted from the budget. Nonetheless, satellite oceanography is an important field of endeavor, and will continue to be so in the future. We take this report, then, as an important and focussed set of recommendations for the near-term direction of the NASA satellite oceanography program. As such, the report is valuable in helping us develop a realistic rationale for the continued development of our nation's space-based observations for the oceanographic community. The members of the NOSS Science Working Group and their many interested colleagues who freely offered their help are to be congratulated for their work; NASA and the entire oceanographic community can only benefit from their efforts, and we are grateful for their aid.

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# FOREWORD

*Icing the Pole*
*or in the torrid clime,*
*Dark — heaving — boundless*
*— endless and sublime*

*Byron*

The poet wrote these lines at the beginning of the modern age of scientific exploration of the oceans. For centuries previously, geographic discovery and exploitation saw many maritime expeditions devoted to rounding out knowledge of the globe; many useful scientific observations also resulted. For example, until not too long ago the best temperature measurements and depth soundings in some oceanic regions were those of Captain Cook, dating from the eighteenth century. In even more remote ages, people used the seas extensively—for trade and emigration routes, for food and mineral resources. Much of the lore of the sea has very ancient roots.

*Icing the Pole,* sings the poet. The ice-covered Arctic Ocean is not at all a tranquil, negligible sea. It exchanges waters primarily with the northern Atlantic Ocean, and this exchange is an important part of the heat budget and annual cycle of these waters. Were the Arctic Ocean ice free, quite different oceanic and climatic regimes would prevail in the Northern Hemisphere. Antarctica is a huge continent covered with a vast ice sheet, the earth's crust being pressed down by the weight of the ice to far below sea level. Should the deep southern oceans warm, or the circulation change, some of the antarctic ice sheet might be subject to catastrophic change. The breaking free and eventual melting of the West Antarctic Ice Sheet is one of these hypothesized catastrophes. The worldwide effect on sea level and on the oceans in general would be great.

The ***torrid clime*** is the home of very large-scale and important oceanic phenomena, such as the great systems of low-latitude surface currents, under currents, and counter currents. They appear and disappear, perhaps in some relationship to atmospheric changes, resulting in oceanic conditions important to man, such as great changes in fish breeding conditions and recruitment of fish stocks. The changes in fishing grounds near Peru and off the east coast of Africa are a few of the important examples.

***Dark — heaving — boundless — endless,*** says the poet. Byron was a sailor; he knew and loved the vagaries of the sea and respected its violence. His view, however, was restricted to the surface. Today, ships, buoys, bottom instruments, and submersible craft allow us to penetrate the darkness and to sample directly the chemical and physical processes of the sea. The geological, geochemical, and biological explorations of the sea bottom have led to incredible contemporary discoveries and new questions that the poet could not have imagined; the "living" sea floor to this day is hardly fathomed, hardly understood and explained. But the ocean is still rather dark, in the sense of yet withholding many details of its dynamics, its interaction with the earth below and the atmosphere above; the wide variety of life it contains still holds much to discover and understand. Its heavings and churnings are better understood than before, but are not yet satisfactorily predictable. Great storms brew up suddenly and wreak havoc on shipping, on fisheries, on human works along the ocean shores and pose sudden dangers to off-shore mineral and energy exploitation. Boundless and endless it no longer is, in the sense that we have the technology to explore all the depths, the remote niches, and even to observe its upper surface global and synoptically. Not many of these resources are at their optimum stage of development, nor are they satisfactorily cost-efficient—in fact, they are very costly indeed. The information they are capable of gathering, however, ***is*** cost-effective in terms of the need of mankind to know and understand the oceans and their vagaries.

***Sublime***—what did the poet intend by this word of so many meanings and shades of color? Taking the ancient roots of the word, he may have meant "raised to a high level," perhaps unreachable, exalted in its mystery. Perhaps he meant to evoke the grandeur of its relationship to the human drive to explore, understand, conquer. One possible meaning is related to high intellectual worth. This is certainly a contemporary facet of the ocean sciences. Not only is knowledge of the oceans of great intellectual value, but the practical value cannot be minimized. Moreover, the intellectual and practical challenges are great and stimulating.

The material in this report derives from a number of sources, first of which were the discussions of the NOSS Science Working Group, established to advise the National Aeronautics and Space Administration on what important ocean science programs could be accomplished or supported through a specific spacecraft program, the National Oceanic Satellite System (NOSS). The discussions grew to encompass remote sensing possibilities from other kinds of spacecraft and the use of spacecraft as communication links with drifting buoys. Direct shipboard, buoy, or other kinds of oceanographic and biological observations would be needed not only as validation or quality control of spacecraft indirect observations, but also as observing partners of the satellite systems. The latter was seen as necessary to establish the composite observing technology needed to address the major ocean science problems. As time went on, it was also recognized that a broader survey would be needed of satellite observing possibilities to support a variety of ocean science needs.

Many colleagues contributed special materials to this compilation, especially to Chapter 2, and special thanks are due them for their efforts. Chapter 2 has the appearance of a shopping list. It is intended to illustrate a variety of good scientific applications and only a limited attempt has been made to integrate material from diverse contributors, or to reduce overlap. Some useful and germane material from other published reports and studies has also been quoted or paraphrased.

To provide a framework and a context for such material, some one person had to serve as organizer of the train of thought, editor of the material, and supervisor of the final production. The undersigned, in the capacity of staff support for the NOSS Science Working Group, assumed these tasks, and takes full and sole responsibility for the sins of omission and commission that the expert reader will discover. The report, however, has been reviewed by the NSWG and represents a consensus on what is needed, what can and should be done and, insofar as it is possible to specify, how.

This report is addressed not only to those interested in the application of remote sensing to the ocean sciences, but also to colleagues in administrative and management positions in the federal agencies who have the unenviable task of deciding how to partition rather limited technical, human, and fiscal resources among the many worthy claimants for federal programs and support.

Finally, the rules of the game have changed. NOSS has been deferred, probably permanently in the form discussed last year. The NOSS science planning exercise, however, has focussed attention on the important opportunities to oceanic sciences research of space-based remote sensing, as new tools, or as crucial complements to non-space technology. The Working Group, constrained to concern themselves with NOSS per se, however, also found it important to discuss some of the wider applications of remote sensing.

Moreover, the compiler felt that it would be useful to express some thoughts concerning the continued development of space-based observing techniques for the ocean sciences. The final section of this report, then, is an attempt to set down some reasonable and realistic possibilities, based on the extensive recent experience with Seasat A, Nimbus 7, and the science planning efforts for NOSS.

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# SUMMARY


- Satellite-borne observing and communication systems offer a variety of techniques to observe and/or map qualitatively, with high-resolution, many oceanic features of importance, and to make measurements that are the basis of quantitative information.
- Satellite techniques, however, are limited essentially to surface manifestations and hence there will continue to be a strong need for direct measurements using ships, buoys, bottom moorings, etc., as well as for subsurface remote sensing by acoustic methods.
- The information derived from satellite observations is best used in close coordination with direct observations, for the latter are needed to provide the high time and space sampling needed, the highest accuracies, and also to serve as validation/control of the information inferred from satellite observations; the former provide the wide areal coverage, long-term and repeated observations necessary to build up valid statistical data series for such physical quantities as surface wind or stress fields, surface temperatures, ocean-atmosphere heat budget, and the time and space characteristics of the range of scales of oceanic circulation.

- Satellite techniques also facilitate widespread direct observations through the use of satellite-borne data collection and location systems, communicating with such platforms as drifting and pop-up buoys, ships of opportunity, and remote stations.

- There are several large-scale national and international experiments being planned in the context of the World Climate Research Program for which satellite techniques offer valuable and in some instances unique capability: a large-scale study of the heat budget in the North Atlantic (Cage); a tropical ocean-atmosphere experiment with emphasis on the Southern Oscillation; and a general circulation experiment for which TOPEX (satellite radar altimeter topographic experiment) and extensive use of drifters tracked with satellite techniques would offer considerable unique contributions.

- There is a large variety of smaller-scale regional or site-specific oceanic processes that could be studied effectively with the use of satellite techniques in conjunction with direct observations.

- The color scanner has proven to be directly applicable to many studies of biological processes in the surface waters; the images have also proven to be valuable for mapping and studying some features of oceanic circulation. Color scanner information may also prove to be invaluable for some studies of atmospheric constituents, e.g., aerosols.

- Surface and subsurface drifters, tracked with satellites, which also collect direct measurements, are evolving to the point where substantial experiments seem possible in the near future to study important circulation models and features. Technical development is already under way and should continue, with the goal of deployment of advanced drifters for specific studies. The satellite data collection and platform location system (DCLS) requirements and designs need further study to ascertain what requirements could be met by existing systems (e.g., Argos and the systems on the geostationary satellites) and what further developments might be needed to serve oceanic needs even better.

- There is much work to do in acquiring, editing, and formatting important historical data sets, such as winds from ships, and sea-surface temperatures, as well as extensive satellite data sets which have not yet been put into accessible form. Moreover, there is a great need to begin to compile a user-interactive data catalog for oceanic sciences to facilitate better use of the kinds of data fields just mentioned. One way to meet these needs is to establish a dedicated data system for oceanic sciences oriented explicitly to the user of data and information derived therefrom. Such a facility would then support future extensive satellite oceanic science experiments and programs.

- TOPEX seems to be the ripest satellite technique for early implementation as a major research effort. Possibilities should continue to be explored of an early flight program, even if all optimal conditions cannot be met simultaneously.

- The possibility should be investigated of implementing a special pilot data processing effort for the operational sea-surface-temperature observations. This effort should attempt to include corrections and data quality procedures not practicable in the operational data processing system. Products of such an effort would be valuable research contributions.

- The possibilities of including a radar scatterometer and/or color scanner on NOAA operational polar-orbiting satellites are being investigated. These represent important opportunities to provide extensive data sets to evaluate the needs for related direct control observations, and to provide extensive and valuable, even if not optimal, data sets for research.

# CONTENTS

# ILLUSTRATIONS

# GLOSSARY OF ACRONYMS AND OTHER MYSTERIOUS NOMENCLATURE

**Argos** This is the name of the French satellite-borne data relay and platform location system designed for the Global Weather Experiment 1979. Its primary function was to locate and track constant-level balloons which were to have been flown in the Southern Hemisphere to obtain winds and temperature. Its design also permitted use of many other kinds of platforms, such as ocean and ice buoys. The name (French spelling) refers to the one hundred–eyed monster guarding the heifer IO in Greek mythology. The system flies on the NOAA Tiros N operational, polar-orbiting satellites, and will continue until at least 1986.
**AVHRR** Advanced Very-High Resolution Radiometer, an operational instrument on the NOAA series of satellites designed to observe the surface in the so-called window regions. Full resolution is about 1 km; there is insufficient on-board recording capacity, however, to store full-resolution observations for the whole globe, so processing is done on-board to produce 4-km resolution global coverage. For special work, the full resolution observations can be recorded on-board for about 20% of the globe. Also, 1 km resolution data are transmitted continuously in real-time to receivers in an experiment area.

**Cage** This is the name of a major internationally organized experiment being discussed for the mid-1980s. The proposed observational program would enclose the North Atlantic Ocean and the atmosphere above to measure the heat flux and its divergence, hence the name.

**DCLS** Data Collection Location System, a generic name for a satellite-borne system to receive relayed data from platforms and to allow determination of their position by processing of the signals. Argos location is accomplished through an analysis of the Doppler shift of the received signals. A somewhat different system was discussed for possible flight on NOSS, in which two antennas on the spacecraft would constitute an interferometer; analysis of the received signal would yield the position of the transmitter; Doppler analysis would have been used to resolve the ambiguity inherent in the interferometric analysis.

**ERBE** Earth Radiation Budget Experiment, planned for the mid-1980s. Narrow- and wide-angle radiation sensors will be flown on two NOAA polar-orbiting satellites and on a third research satellite. Special attention is being paid to calibration procedures to assure that the required accuracies will be maintained; the multiple-satellite system will assure that enough sampling will take place during one day to reduce the diurnal bias which has hampered analysis of observations from all previous radiation budget experiments.

**GEOS** Geodetic satellites, with accurate orbital determinations. A radar altimeter was flown on GEOS 3 as the first full space test of this technique for measuring the topography of the ocean surface.

**GOASEX** Gulf of Alaska Experiment, during which much direct data were obtained of surface winds, for comparison with Seasat scatterometer observations.

**GOES** Geostationary Operational Environmental Satellite, operated by NOAA. There are two satellites, one over the eastern U.S.A., the second over the eastern Pacific. The main observations are high-resolution images in visible and infrared, for analysis of cloud occurrence and types, their movements, and as structural clues to atmospheric dynamics. The two GOES spacecraft now in operation also include experimental infrared vertical sounders, VAS (see below), the observations of which are used to infer temperature and humidity profiles.

**ICEX** Ice Experiment, a report of a study group convened to outline the major problems in sea and land ice that could be addressed through satellite techniques.

**ITCZ** Intertropical Convergence Zone

JASIN Joint Air/Sea Interaction Experiment, conducted in the North Sea. Seasat passes over the JASIN array permitted a comprehensive set of intercomparisons between direct observations and information inferred from the satellite observations.

**LAMMR** Large Antenna Multichannel Microwave Radiometer. This instrument is a direct descendant of the previous microwave radiometers, which proved their utility in mapping the surface (e.g., for ice) in cloudy conditions, and in obtaining useful surface temperature observations. The LAMMR was designed to provide a higher spatial resolution than had been obtained before, to improve the usefulness of the sea-surface temperatures, and to reduce the size of the coastal zone where land effects degrade the desired signal.

**MIZEX** Marginal Ice Zone Experiment

**NASA** National Aeronautical and Space Administration, an agency of the U.S. Government

**NESS** National Earth Satellite Service of NOAA (National Environmental Satellite Service until recently)

**NOAA** National Oceanic and Atmospheric Administration of the U.S. Department of Commerce

**NSF** National Science Foundation, an agency of the U.S. Government

**SEQUAL** Seasonal Equatorial Atlantic Experiment

**SOFAR** Long-range ranging technique using the sound channel and underwater floats; the exact derivation of the name SOFAR is obscure, but it can be inferred to have been derived from Sound, Far, and Ranging.

**STD** Salinity, Temperature, Depth sounding, accomplished with sample bottles and subsequent chemical analysis, or with automatic profiling equipment.

**TIROS** Television InfraRed Operational Satellite, the first series of NOAA meteorological satellites.

**TOPEX** Topographic Experiment, using a precision radar altimeter, proposed for the mid-1980s to study ocean dynamics.

**VAS VISSR** (see below) Atmospheric Sounder, now being flown on the two NOAA GOES satellites. The reduced signal at geostationary distance is compensated for by time averaging, to produce a signal-to-noise ratio similar to that of the instantaneous observations made on the polar-orbiting satellites. An important advantage of VAS is to be able to concentrate on a region of interest and build up a coherent time-series of observations during fast-breaking mesoscale meteorological events.

**VISSR** Visible, Infrared Spin-Scan Radiometer used on the NOAA geostationary satellite (e.g., GOES) to image the earth in visible and infrared. The spin of the satellite supplies the lateral scan across the earth's disk, while the vertical scan is accomplished through a stepping mirror, with a cycle time of about 25 minutes. Smaller portions of the disk can be scanned at a more rapid rate.

**XBT** Expendable bathythermograph, a device which, having been launched from a ship (stationary or under way), drops through the water and sends back through a fine wire temperature information as a function of depth. The sonde continues to sink when the full length of wire is played out, hence "expendable." Air-dropped XBTs are called AXBTs. These instruments make it economically feasible to monitor upper-layer temperatures over some important oceanic regions.

# 1
# INTRODUCTION

The ocean processes have traditionally been investigated by sampling from instruments *in situ*, yielding quantitative measurements that are intermittent in both space and time. The past two decades have seen the development of new observing systems such as the STD, current meters, and SOFAR floats. These devices give a continuous record in one dimension, either instantaneously in the vertical or at a fixed point, or approximately moving with a water parcel. Arrays of these instruments have greatly increased our awareness of the space-time variability in the oceans, be it due to internal waves, mesoscale eddies, or fluctuations in the general circulation itself. The need to obtain proper ***sampling*** of the averaged quantities treated in our analytical and numerical models is at present probably the most significant limitation on advances in physical oceanography.

In principle, space-based techniques can offer substantial information important to this four-dimensional jigsaw puzzle. Global coverage of broad-scale surface features such as wind stress, sea level, and temperature at time intervals which are short enough to be effectively continuous gives an enormous potential advantage over shipborne techniques. High-resolution snapshot images of temperature or color or microwave emissivity allow unique visualization of near-surface processes such as internal waves or eddy formation; such visualizations can greatly extend the interpretation of conventional measurements, and allow considerable economies and a new kind of strategic planning of ship operations. Communication with sensors on fixed and drifting buoys, and the location of nonfixed systems through satellites make possible all sorts of composite subsurface measurement systems which would otherwise be quite impracticable.

*Remote sensors operating from the vantage point of space will never replace direct measurements and acoustic remote sensing, because the ocean is effectively opaque to electromagnetic radiation, but satellite remote-sensing observing and data relay and platform location techniques should play a substantial role that needs to be systematically recognized and exploited in future programs of ocean sciences research.*

Such exploitation requires a developing synergism between specific space-based techniques and missions, on the one hand, with research experiments on important oceanographic problems that benefit from those techniques, on the other. The uncertainties associated with inference from remote sensing, and the difficulties of reconstructing the overall picture from observations *in situ* imply that the acceptance of new information will come only after a painstaking program of observing system intercomparison and confidence-building case studies. These will require long-range commitment by leading oceanographic scientists and satellite instrument specialists.

The extensive experience over the last two decades with meteorological satellite systems, used in close coordination with ground-based networks to provide a space-based/surface-based composite observing system, gives us considerable insight into analogous prospects for support of ocean science research, as well as into what kinds of direct ancillary ocean observations are necessary, what trade-offs must be dealt with, and what kinds of special data management efforts should be undertaken to facilitate the research access and use of the observations.

*Recent experience with sensors on GEOS 3, Seasat, and Nimbus 7 designed for ocean observations underline the need to include from the beginning explicit planning for validation/control observations, and a substantial data collection effort. To do otherwise would risk not extracting the full advantage of the very large investment in the satellite portion of the system.*

New observing tools can transform the basic perception of old problems, but only after their interpretation has been established, necessary corrections have been applied, and calibrations and error estimates are known. There are few applicable standard techniques for "surface truth." Indeed, the space-derived information has fundamentally new characteristics, such as horizontal averaging over larger regions and the feasibility of averaging over longer times (e.g., through repeat observations), so that it is attractive as a unique complement to information derived from direct observations. The orderly evolution of composite systems also needs long-range vision and stability of institutional arrangements which transcend the traditional boundaries of funding agencies. The process of assimilation and adjustment to these new opportunities will be a long and sometimes painful one.

This document attempts to sketch a vision of some of the scientific problems in which this endeavor should be embedded. It is intended to stimulate discussion rather than present a final judgment. It cannot describe all the important potential applications, nor list the provisos and details that need to be considered in final evaluation of the prospects for each problem, but it may serve as a framework for the ongoing evolution of concepts and priorities of a realistic program.

# 2 APPLICATIONS OF SATELLITE-BASED OBSERVATIONS

During the discussions of the NOSS Science Working Group, a number of research areas were discussed for which satellite techniques offer either valuable complementary information to ship and buoy direct observing techniques, or represent the only feasible way to obtain the information needed. In addition, several other planning studies are under way in connection with the World Climate Research Program. The feasibility of at least one major ocean experiment is being examined internationally. Others are under discussion in the U.S.A. These suggestions are not idle suggestions; they relate closely to the research interests of individual scientists, based on what they would like to be involved in themselves should the opportunity arise.

The following descriptions of possible research activities are not ordered according to priority, but illustrate a range of important and challenging scientific applications. Many such research objectives could be met by a few satellite flight programs, and there are many ways in which observing systems may be combined on any particular flight. No attempt is made here to discuss such matters.

## 2.1 Models

Phenomenological and analytical techniques and models play important roles in providing required detailed descriptions and also represent a highly useful and valid approach to the physical understanding of many important oceanic processes. The data series discussed in this report as necessary will be of great importance to further development and verification of all types of models.

Increasingly, numerical models of various types are becoming a powerful tool by which diverse observations of the ocean are tied together to form and test a coherent picture of the state of the ocean and the processes at work. There are nearly always insufficient data to determine uniquely all the fields needed. The simplest model is a diagnostic or universal one, which explores the range of possible interpretations subject to certain kinematic constraints (such as geostrophy, or conservation of mass, salt and temperature). A number of other model types have been developed which start from the equations of motion and are dynamically and thermodynamically consistent, though not necessarily *correct* descriptions of the real situation: some of these address the general circulation in the world ocean; there are eddy-resolving models of the circulation in specific ocean basins; some models aim at the transient response to changes in atmospheric forcing near the equator; there are one-dimensional models of the upper mixed layer and seasonal thermocline; and there are storm surge and tidal models for specific coastal waters. Each of these requires specific inputs and makes predictions which may be used for validation.

For example, a general circulation model normally assumes fields of surface wind stress, surface temperature, and net precipitation minus evaporation, and predicts time mean fields of subsurface temperature, salinity, and velocity, together with sea level and surface heat flux. Numerical experiments can determine the sensitivity to reasonable variations in model parameters such as eddy diffusivity, and then the available data are used to test the overall consistency. The more reliable the information that is available, the better. Specific types of measurements will have greater or lesser impact depending on the problem at hand. The surface stress, properly time-averaged over several weeks or longer, and sufficiently accurate to determine the distribution of its curl on the scale of the oceanic phenomenon under consideration, is nearly always a significant input; however, for mixed-layer models greater time resolution may be required, and near coastlines it is the stress itself rather than its spatial gradient which is most important. Time-averaged surface temperature is usually also a required input; however, unless validation against surface heat fluxes is involved, the precision available from historical merchant ship data is normally adequate. Fluctuations in surface temperature may be a valuable validation tool in time dependent problems, and synoptic measurements sufficiently accurate to determine them are potentially important. The near-surface geostrophic velocity is another validation variable, intimately connected to gradients in sea level after tidal oscillations have been eliminated. It is the large-scale averages most naturally provided by measurements of sea level which are most valuable for all except local process studies.

For investigations of the large-scale time-dependent response of the near-surface waters to varying wind stress, a first approximation is to ignore the motion of the abyssal waters and to consider the movement of the layer above the thermocline as a vertically coherent unit. This is a central problem in the interannual variations of global climate, centered in the tropical ocean. The combination of wind stress and sea level alone would then provide a major test of the dynamics of the models; with the addition of sea-surface temperature to test the thermodynamics, remarkably complete intercomparison would be possible.

In most cases however, direct subsurface measurements are needed to provide an adequate range of validation variables to test model performance. Near-surface temperature and heat storage can be measured from surface drifters using satellite communications as an essential link. Subsurface velocities from constant-level floats can again provide the large-scale long-time averages so important for most studies. Satellite communication links and position finding can greatly extend the possibilities here. On the other hand, there appears to be no substitute for ship-based profiles of temperature and salinity and radioactive tracers which provide essential information about the volumetric distribution of different water masses. Examination of the models designed for each of these specific problems yields insights into the information gained from observations of any given accuracy, sampling density, and overall coverage, which where possible are qualitatively reflected in what follows. More thorough examination of these issues is necessary before a complete picture of the potential impact of space techniques on oceanography can be constructed.

## 2.2 Generic Observations

There are a variety of observations which, if made continuously over several years and processed and reduced to formats designed for research use, would supply the needed coherent data sets for many specific research problems and for test of models, as discussed above. Moreover, such data sets would, if continued operationally, form the bases of extraction of indices useful for long-term monitoring of variability. The existence of such coherent and long-term data sets is of paramount importance in atmospheric research. Oceanic research would be similarly benefited by establishment of regular observations.

*Space-based techniques could contribute significantly to provision of long-term, internally consistent observational series. However, the satellite information would be even more valuable if reliable ties could be established to the conventional historical data bases. The establishment of such reliable connections, and the careful editing of the historical data would be far from a routine trivial task.*

### 2.2.1 Wind Stress

The wind stress at the surface is one of the major driving forces of oceanic circulation. There are no *systematic* observations with which to test the performance of various models of ocean circulation and ocean response to the atmosphere. Ship observations of wind provide some coverage in regions served by commercial shipping; ship observations, however, are noisy (i.e., may contain undetectable errors) and uncalibrated (e.g., for ship effects) and must be processed carefully before use.

In the opinion of scientists who are trying to develop better models of the ocean circulation, one of the greatest needs, at present, is a coherent, calibrated long-term data set of surface stress or wind over at least the tropical zone, and preferably over the globe. The Seasat data processing effort and the experience with the validation program indicate what explicit measurements must be made *in situ* to facilitate the use of the basic observations. The Seasat data offer an enticing glimpse of future routine wind stress/wind velocity observations globally. But can satellite techniques really supply the information with enough ancillary data for its interpretation? Many special studies will be needed to improve the interpretation of scatterometer observations (i.e., to translate the radar backscatter cross section of capillary waves into stress/speed) and also to identify situations in which there might be other physical or biological factors contributing to the backscattered signal, i.e., to identify reliably the various surface effects that influence the backscatter, and to make adequate corrections.

For example, the return signal from a scatterometer depends on the presence of surface structures with scales in the centimeter range; the usefulness of the scatterometer in measuring wind speed depends upon variations in the intensity and density of these structures as a function of wind speed. Several different kinds of structures at these scales can be discerned and they may vary with wind stress in different ways; the scattered response lumps them all together.

One kind of structure involves groups or trains of capillary-gravity waves at these scales, generated directly by the wind stress and perhaps to some extent by weak resonant wave-wave interactions from larger components. At low wind speeds, the local amplitude of these wave trains may not vary strongly with wind speed—they may reach a local saturation quite quickly—but the fraction of total area covered by them will surely increase with the wind stress. Also at these scales will be found harmonics of longer, short gravity waves which can be relatively sharp-crested and rich in harmonics. Finally, at these scales also will be found Fourier components associated with the deformed profiles of short, breaking waves as well as the parasitic capillary waves on short gravity waves with relatively sharp crests.

Not much is known in detail about the distribution of these structures and the way that this varies with wind stress. Although our knowledge is sketchy, certain simple properties are reasonably well established. First, the density of microscale breaking waves (wavelengths on the order of 10 cm) increases with wind stress but the amplitude at breaking decreases with wind stress. These profiles are substantially deformed during microscale breaking and contain harmonics at the scales responsible for backscattering. The time scales for generation and decay of wave trains at this scale are short, seconds or tens of seconds at most. Short gravity waves, on the other hand, have growth and decay times longer than this so that (as is usual in the ocean) if they are accompanied by a dominant longer gravity wave these short waves will be substantially modulated in amplitude and also in wave number by the dominant wave. Short gravity waves are pushed close to saturation near dominant wave crests and this results in a substantially increased density of microscale breaking, parasitic capillary waves, and harmonics of the short gravity wave themselves. On the other hand, in the troughs of the dominant wave, the desaturation of the short gravity waves reduces these. These modulations provide the basis of operation for the dual-frequency scatterometer radar.

It is this melange of structures that provides the back-scattered return. The return is clearly a function of wind stress (more properly, $u_*/c$, where $u_*$ is the friction velocity and c is a representative phase speed of the structures) but observational results still give a great deal of scatter. Enough is known about these structures to be confident that they are also influenced strongly by the slope of the dominant wave present, ak, or Huang's "significant slope" parameter. This dependence is not taken into account in analysis of scatterometer results in which its influence is ignored.

It is evident that there is a considerable need for further research in this area to establish better the characteristics of these small-scale structures, their distribution on the ocean surface, their appearance in response to short-wave/long-wave interactions, and so forth. Experiments and observations are difficult. Conventional probe measurements give very restricted information and are extremely difficult to interpret because of the Doppler shifting produced by the orbital velocities of longer waves. Instantaneous spatial definition of the water surface, even in a restricted region, is a tricky problem. Nevertheless, these problems are worth doing. If they were easy, they would have been done already!

Some significant and feasible applications of the wind stress data obtained from satellites would include:

#### 2.2.1.1 Numerical modeling

The general circulation, the transient response to atmospheric forcing near the equator, and the generation of storm surges in coastal waters are some of the many important problems for which the numerical model is a powerful analytical tool. Of particular interest is the transient response near the equator, for which, if the wind field is known, the number of tunable parameters in a typical model becomes quite small.

Even with a knowledge of the wind stress, a major uncertainty remains in that we lack the data to initialize a model. This problem can be reduced by focusing on aspects of the ocean circulation that are more directly wind-forced and where the response time is relatively short. One might hope to initialize by running a model for a longer period of time with known winds and verifying the model against data collected during the period corresponding to the end of the model run. The equatorial upper ocean would be preferable to midlatitudes or the deep ocean, both because the response time is shorter and because aspects of the circulation that are not directly wind-forced (e.g., eddies resulting from instabilities, thermohaline effects) appear to be less significant there. Even so, at least two years of wind data would be needed for a model run long enough so that the initial conditions would have little influence (cf. Cane, 1979). Reliable ten-day averages of surface wind on spatial scales of 100 km would give a sufficient knowledge of the field.

The modeling effort envisioned here would require a significant increase in model development activity and in computational resources; these needs and possible ways to meet them are under discussion in respect to programs of other agencies (ONR, NSF). In addition, data taken carefully *in situ* for verification would be required. The NSF–sponsored Seasonal Equatorial Atlantic experiment (SEQUAL) in the tropical Atlantic is indicative of the measurement program needed: moored current meters deployed for long periods of time to establish temporal and spatial current variability, inverted echo sounders, and other mass field measurements to monitor variations in dynamic topography.

#### 2.2.1.2 Sverdrup experiment

Modeling of the seasonal and interannual variations in the ocean circulation is (at present) a hindcasting problem in which all historical wind data may be utilized. Even in this case, data coverage is often inadequate to answer zero-order questions. For example, two very recent studies of the North Equatorial Countercurrent (Meyers, 1979) include calculations of the Sverdrup transport of this current—a linear function of the wind-stress curl—that differ by a factor of two; this is not a surprising matter in view of the paucity of wind stress data and the dependence of wind stress curl estimates on the grid spacing. The Sverdrup balance was first derived in a study of the North Equatorial Countercurrent in 1947. It has since become the central concept in theories of the large-scale ocean circulation, but direct observational evidence for it remains ambiguous. Leetmaa, Niiler, and Stommel (1977) and Leetmaa and Bunker (1978) concluded that the observed North Atlantic circulation is consistent with the Sverdrup relation, but uncertainties in estimates of both ocean transports and wind stress are large. In particular, calculation of Sverdrup transport requires a knowledge of derivatives of the wind stress. In many regions of interest (e.g., the ITCZ, over the Gulf Stream), the wind system exhibits marked variations on scales of 100 km. Hence, Sverdrup transport estimates require measurements of the wind stress at the scatterometer footprint scale of ~50 km.

The Sverdrup balance is a steady state relation while winds and currents vary temporally. This raises two obvious questions: (i) Does the Sverdrup balance hold, say, for all time scales longer than some time scale T? (ii) If time dependence is added to the simple linear, inviscid, quasi-geostrophic Sverdrup physics, would agreement improve?

Answering these questions requires a knowledge of the wind stress on time scales longer than T; it would be of interest to take T to be one month. Further direct observation of ocean transports are required. The North Equatorial Countercurrent would be a favorable location: there is a strong localized signal there and it is far enough from the equator to expect that quasigeostrophic dynamics will hold. Recent work in the Pacific shows that geostrophy gives satisfactory estimates of current speed so standard hydrographic measurements would suffice, although some direct current measurements would be desirable, particularly in the abyssal waters.

### 2.2.1.3 Mesoscale variability

The most energetic mesoscale oceanic eddies are found in the vicinity of strong currents (Gulf Stream, North Equatorial Current) and probably have their source in instabilities. Over most of the ocean, the level of eddy energy is lower; two recent studies (Willibrand, Philander, and Pacanowski, 1980; Frankignoul and Müller, 1979) have concluded that these eddies could be attributed to direct forcing by the variable winds. Their conclusions require some assumptions about the nature of wind spectra. Scatterometer data will go a long way toward replacing these assumptions with solid data, but some field work will also be necessary to extend spectra to finer time and space scales than a scatterometer will provide.

It has also recently been suggested (Frankignoul and Müller, 1979; Müller and Frankignoul, 1981) that a significant part of the eddy field of the open ocean away from strong boundary currents is directly forced by fluctuations in the curl of the atmospheric wind-stress. This conçlusion was based admittedly on a few observations which show a significant coherence between a seasonal modulation of atmospheric and oceanic fields and on a theoretical evaluation of the oceanic response to forcing by a fluctuating wind-stress field. The theoretical estimate used a model wind-stress spectrum which extrapolated the observed spectral slope at scales on the order of 1,000 km down to scales on the order of 100 km.

To substantiate these suggestions it is extremely important to determine accurately the space-time structure of the wind-stress over the ocean on eddy scales. This would require a spatial resolution of approximately 10 km and a time resolution of approximately three days. The wind measurements should cover two open oceanic regions of size 10° x 10°, one in the Pacific and one in the North Atlantic. The regions should be chosen to coincide with regions of long-term sustained oceanic measurements. Such choice would facilitate direct proof of wind-stress forcing by correlation and response techniques. A suitable region in the North Pacific is the site of P. Niiler's five-year mooring. In time, the measurements should cover at least one year (to estimate seasonal variability), but should be longer for correlation and response studies.

#### 2.2.1.4 Storm surge and wave modeling

Storm surge and/or wave forecasts are often desired for relatively small regions; specialized wind analysis schemes will be required to treat high temporal and spatial resolution. Storm surge and surface wave modeling are, most importantly, prediction problems (although there is increased interest in hindcasting studies as inputs to the design of off-shore structures). These oceanic features on the synoptic time scale are more directly and locally related to the wind than is the more physically complicated large-scale circulation. The wind field to drive these prediction models must be forecast; errors in the winds are the dominant source of errors in the ocean prediction.

Improving surface wind forecasts and hindcasts (analyses) is a problem in numerical weather prediction (NWP). However, present NWP models have a rather poor treatment of the planetary boundary layer and are ill-equipped either to absorb surface wind data or to produce a surface wind field. Work will be needed in this area to make effective use of scatterometer data.

### 2.2.1.5 Wind

Improving surface wind forecasts and/or analyses is a problem in numerical weather prediction (NWP). Present NWP models have a rudimentary treatment of the boundary layer that causes inaccuracies in boundary layer and surface wind analyses and forecasts.

Analyses suffer because of the difficulty in combining surface wind observations such as might be inferred from scatterometer wind stress observations with directly observed wind observations made from ships at a variety of heights above the surface. Present techniques normalize all observations to some standard level through a rudimentary boundary layer model.

Forecasts suffer because of the poor method of assimilating surface wind observations through the full depth of the atmosphere. Boundary layer winds at some future time are effected by a combination of surface and upper level forcing. Present techniques for forecasting that upper level forcing do not make adequate use of the large number of surface observations that might come from operational use of a scatterometer.

### 2.2.2. Observations of Sea Level (Radar and Lidar Altimetry)

One satellite-based effort that has been under discussion for some time has been a topographical experiment (TOPEX). The radar altimeters on the GEOS 3 and Seasat satellites have proven that observations of the distance between the sea surface and a satellite can be obtained to a useful precision, and that a wide variety of important oceanographic and geophysical information can be derived from such observations. Accurate knowledge of the satellite orbital quantities and of the earth's gravity potential field (the geoid) is necessary to extract the maximum information from the satellite altimeter observations. These matters, as well as the scientific problems to be addressed by TOPEX, are discussed in detail in the report Satellite Altimetric Measurements of the Oceans, prepared by the TOPEX Working Group, published by the Jet Propulsion Laboratory (March 1981).

Some aspects of satellite altimetry are reviewed briefly here. *Figure 1* illustrates some of the geometry involved, with, of course, the vertical dimension greatly exaggerated. The Seasat altimeter showed a precision of about 10 cm in the measurement of the distance between the instantaneous sea surface and the satellite. It is estimated that this precision has to be increased to something like 2 cm to meet the majority of

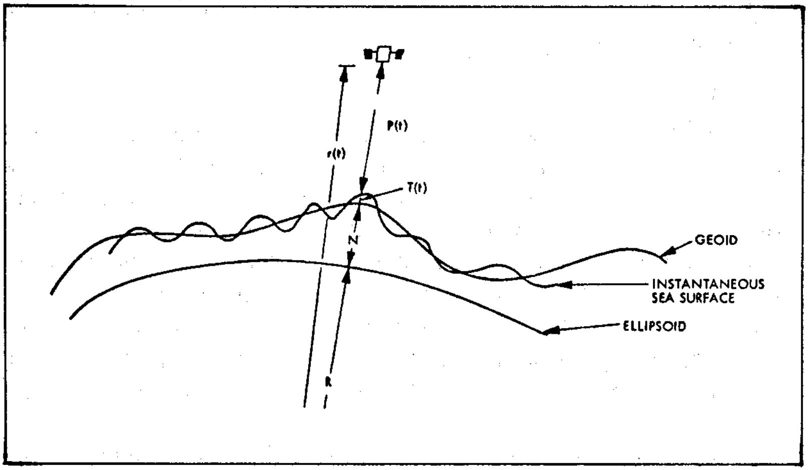



*Figure 1.* Schematic view of the geometry of the satellite altimeter vis-à-vis the reference ellipsoid (related to the geometric shape of the earth, the geoid (based on the actual distribution of the earth's gravity field), and the instantaneous sea surface.

the scientific goals of TOPEX.

*Figure* 2 illustrates the ability of Seasat to discern clearly a major current system (the Gulf Stream) and its short time variability and, moreover, to map the more intensive eddy or ring structures. Thus, a satellite altimeter in a suitable orbit (see TOPEX report for a full discussion) will provide information on major currents and eddies not now easily available.

A geophysical application of great interest is shown in *Figure* 3. The sea surface acts as a gravity level, and mirrors the gravity anomalies that arise from large features of bottom topography. The kind of relative bottom mapping shown here represents significant information for geophysicists studying the dynamics and morphology of the ocean floor.

Another feature of the altimeter is its ability to provide very important and reliable information on the statistics of ocean waves, in particular the significant wave height, $H_{1/3}$. This ocean surface variable is very important for practical purposes, e.g., for marine operations, and also for the study of the development, propagation, and effects of such ocean events as major storm surges.

The radar altimeter could also provide useful information on the topography of the great continental ice sheets of Greenland and Antarctica, which is difficult to obtain by conventional geodetic leveling. While it is true that the satellite orbit for such observations would be inconsistent with the

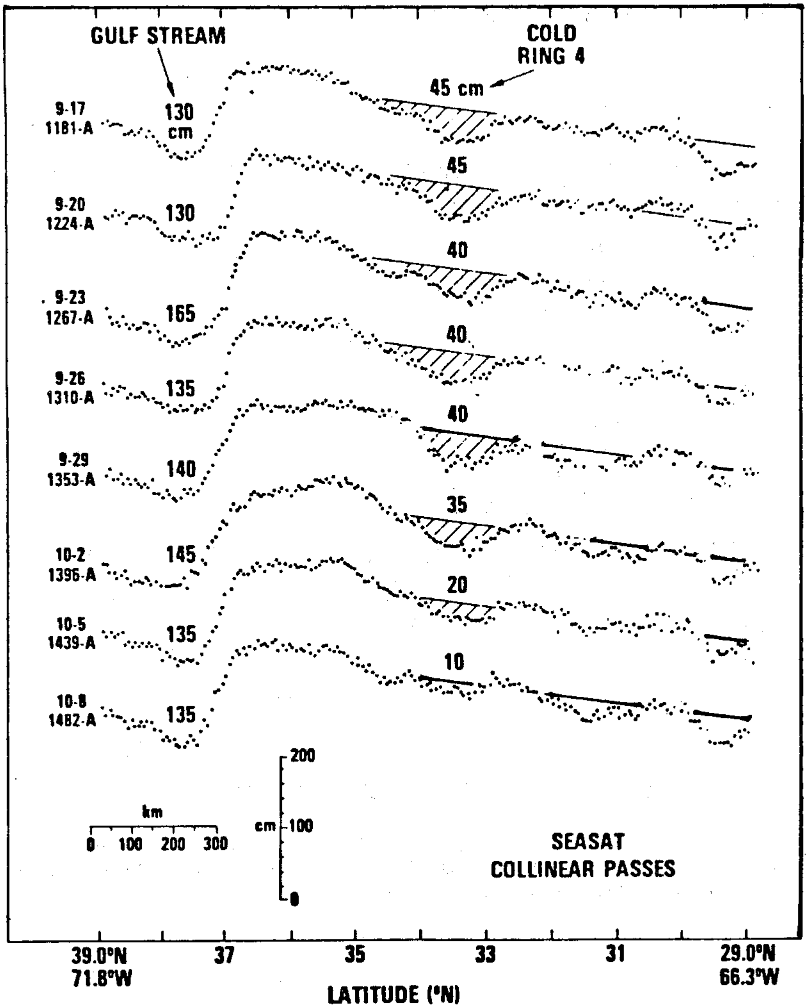



*Figure 2.* Seasat "frozen orbit" passes over the western North Atlantic. The Gulf Stream dynamic trough and ridge are clearly depicted, along with a cold ring that was identified positively by ship observations. Other structures are seen that may also be rings.

optimal requirements laid down for TOPEX, it perhaps also is true that it would not be cost-effective anyway to try to combine all possible missions for a particular instrument on one satellite flight program.

For detailed information on TOPEX and its applications, the reader is referred to the JPL report cited above.

The possibility of a lidar altimeter has been discussed, in particular for studies of ice. The present lasers, however, do not have a long-enough lifetime (i.e., numbers of possible pulses) to be practicable for space flight

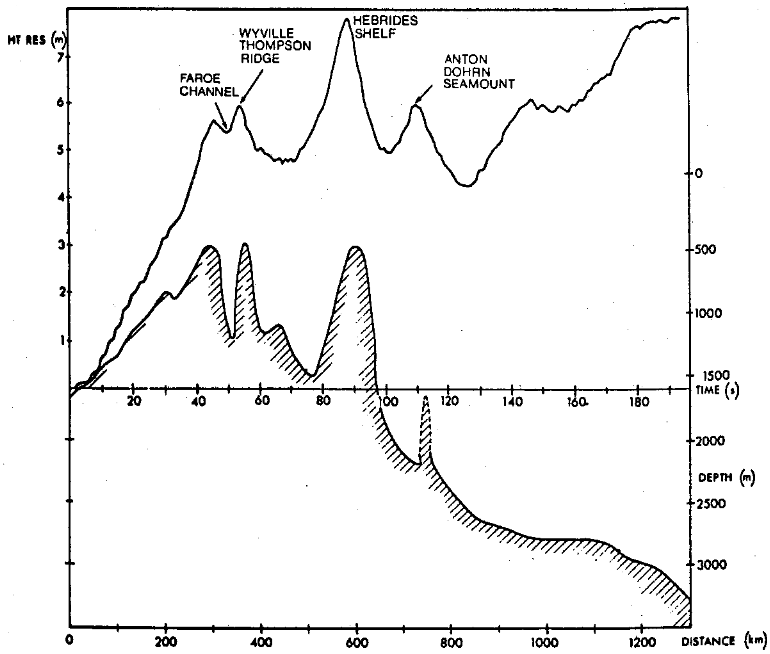



*Figure 3.* A Seasat pass over the eastern North Atlantic, showing the residual sea-level anomalies after removal of other signals. The surface shows a strong and geophysically useful correlation with bottom topography.

for continuous observations. It is likely, however, that some short-term tests will be carried out on shuttle flights.

### 2.2.3 Sea-Surface Temperature

The temperature of the sea surface is one of the important physical factors that determine the exchange of heat energy between the atmosphere and ocean; it can be a measure of the heat content of the upper layer; it can also be a useful signal or tracer of dynamical manifestations in the upper ocean layer (e.g., currents, eddies, fronts, upwelling zones). There is a very large body of historical information, mostly gathered from ships, using a variety of data collection methods. The historical data set is noisy, owing to the variety of methods involved, and the inability to decontaminate much of the data or at least to assign reliable quality control flags. The data are also, in some regions, biased in that time and space sampling is inadequate to represent the dynamics of the system.

A reliable and coherent sea-surface-temperature data set is badly needed; it should provide uniform coverage over the oceans and adequate time sampling. Satellite observations are the only feasible way to achieve this. The present meteorological satellite system offers, in principle, the promise of providing high-resolution and good-quality observations, with enough auxiliary observations to identify contaminating signals and enough information to make corrections so that the required accuracy can be obtained most of the time, or at least so that questionable data can be tagged.

Quantitative sea-surface-temperature measurements are needed for study of related ocean features, for determination of heat transports and their variabilities, and for assessment of the heat content of the ocean layers and its variability. Accuracies should be at least 1°C, preferably better, to characterize, for example, the Namias-scale anomalies of the Pacific. Sources of error must be identified, and the errors characterized (e.g., uncorrelated errors that might be reduced by increasing the number of observations or by time and space averaging, or systematic errors that might be correlated in some way with the phenomena being studied). This requirement may demand different processing methods for different applications. For example, a climate analysis can to some extent forgo frequent observations, to be sure that it was uncontaminated by cloud, and have minimal uncertainty from atmospheric water vapor.

On the other hand, for a fisheries application, coverage and gradient information may be paramount, with absolute accuracy of less importance.

Also, patterns of sea-surface-temperature distribution are very useful to identify and study the time and space variability of many features manifested by temperature gradients. Here, high resolution is useful, and should be preserved in the data acquisition and processing. Spatial resolution from polar-orbiting NOAA satellites is 4-8 km; higher resolution is obtainable, but not storable on the spacecraft, and can only be available to direct ground read-out stations. Resolution from geostationary spacecraft is about 8 km. Interfering patterns, such as those from patchy atmospheric water vapor and aerosol, must be identified and removed.

*It may well be that the major burden of obtaining long-term data sets of quantitative measurements will be met by the meteorological operational system, provided that data processing can be improved well beyond the present system, which is constrained by operational consideration to near-real time correction and quality control procedures. That is, a* special *data processing effort might have to be implemented to extract from the operational data stream as much as possible of the useful information and archive* *it in a form most suited for oceanic and climatic research.*

However, there are some oceanographic satellite observing programs for which collocated, coregistered, and time synchronous sea-surface temperature observations are necessary. The color scanner instrument is a good example. Direct, coregistered sea-surface-temperature images are needed here for the optimal interpretation of the images obtained in the various visible bands. Applications of the color scanner are discussed below.

### 2.2.4 Color Scanner Observations

The Coastal Zone Color Scanner (CZCS) operating on Nimbus 7 is providing a most intriguing new data set. The CZCS instrument was planned primarily for biological investigation, but there is evidence from the data set now available that the patterns seen in the images also trace dynamic oceanic features of great interest.

The intended purpose is to depict, using several bands in the visible (and bands in the red and infrared for correction purposes), the distribution of biological and other scattering agents (chlorophyll, and organic and inorganic suspended materials). It has been realized that, in addition, important information is made available on oceanic structures, sea-surface temperatures, and gross aerosol distribution.

#### 2.2.4.1 Biological Applications

Global and selected regional assessment of living marine resources is the ultimate objective of satellite ocean color sensors. It is abundantly clear from years of shipboard experience that ocean areas with the most biota of interest are also areas that are dynamically the most complex and variable. As a consequence, the accurate assessment of living marine resources can benefit significantly from synoptic data that are impractical, or virtually impossible, to obtain from ships alone.

Chlorophyll in the ocean, as an index of phytoplankton biomass, is a fundamental quantity that can be estimated using aircraft and satellite remote sensors. To date, no ecologically significant biological quantity other than chlorophyll has been shown to be quantitatively estimatable by satellite.

Synoptic estimates of chlorophyll are important because phytoplankton variability in space and time is a ubiquitous and important feature of the marine environment. [Phytoplankton variability includes not only the density of organisms but also the number of species present (species abundance) and the distribution of individuals among these species (species equitability), but observations of these factors are hardly accessible to shipboard sensing and are inaccessible to remote sensing.] This variability influences both practical problems associated with sampling and estimating abundance within the environment and theoretical considerations related to the structure and dynamics of phytoplankton ecology. Also, the variability of phytoplankton communities is thought to hold a key to understanding the relative importance of physical and biological factors in structuring the marine food web. In addition, there is evidence that the successful modeling of phytoplankton dynamics, and the predictive linkage of phytoplankton production to higher trophic levels, has so far been limited by a lack of synoptic data and by limited sampling strategies.

A fundamental problem in marine ecology is to establish both the spatial and the temporal scales in which fundamental physical and biological processes occur and to sample the environment accordingly. Ships, aircraft, and satellites provide alternative, and complementary, strategies for sampling the environment. For example, if chlorophyll concentration, as an index of phytoplankton biomass, is the variable under investigation then ship, aircraft, and satellite "platforms" offer the opportunity to obtain diverse, and often mutually exclusive, experimental information. Shipboard data provide continuity with conventional oceanographic research techniques, can be relatively accurate, can include both vertical and horizontal measurements, but are comparatively limited in both space and time. Chlorophyll data from aircraft systems provide rapid spatial coverage of regional areas, can include both vertical and long-track measurements, can be relatively precise (however, accuracies are the subject of ongoing research), but are limited by the logistics of aircraft, and provide linear (as distinct from areal) coverage. Satellite chlorophyll imagery can provide worldwide coverage of cloud-free areas, can provide repeated routine coverage of regional areas (including those areas that are far from our oceanographic research institutions), but are relatively less accurate without concurrent ship or aircraft data, are limited by cloud coverage, and require more complex image and data processing. The key point is that the living marine resources are unlikely to be assessed adequately without the synoptic perspective, the quantitative areal data, and the quasi-continuous temporal coverage provided by remote sensors.

Some early use of the Nimbus 7 color images has shown very promising application to the studies of the food web and to illuminating the relationships between the planktonic distribution and the development of young fish. For example, off the California coast, such information has been used effectively to study plankton distribution and the distribution of anchovy spawning. More detailed studies of these kinds would clearly be important contributions to biological oceanography.

***Therefore, NASA's objectives with respect to ocean color scanners should include:***

- ***A program concerned with global marine ecology. Many nations are competing for various marine resources and as yet there is no sensible*** *perspective, or even a coherent body of information, with which to judge conflicting interests and the magnitude and resilience of the resources. The "ecological boundaries" of the oceans are global in extent and the major regions of productivity widespread yet relatively small in area. These limited, yet critically important, areas are at least partially accessible to satellite observations and study. NOAA has some statutory responsibility here for U.S. waters, and a coordinated effort by NASA and NOAA would have an important long-term pay-off.*

- *Effective data and information transfer from the existing CZCS system to interested researchers and those concerned with living marine resource management. Selective utilization of the already existing data base can be an invaluable and cost-effective method for optimizing the accuracy of the information, resource assessment strategies, and the characteristics of future remote sensing systems.*

- *Development of an improved ocean color scanner (and associated system) that will allow for: additional bands providing further spectral information on the ocean and atmosphere for use in improved data processing algorithms; increased sensor signal-to-noise ratio for improved color gradient detection; accurate sea-surface-temperature images that are coregistered with those from the color scanner for obtaining both temperature and chlorophyll information with a minimum of data processing; operational capability, both in performance and with respect to availability of data.*

### 2.2.4.2 Ocean physical applications

The color scanner images available now also reveal some very exciting potential for broader oceanographic applications. For atmospheric scientists and operational meteorologists, cloud patterns and their time and space evolution represent unique signals of important atmospheric phenomena. The very first application of satellite observations to meteorology was the interpretation of cloud images, qualitative to be sure, but extremely important in delineating areas of important activity and in identifying what kinds of motions are involved. Cloud imagery still plays an important role in depicting in an easily interpreted way some of the important dynamics of the atmosphere, and we use carefully selected clouds as the only way, at the moment, of tracing atmospheric motions (wind) in some regions.

Multispectral infrared and color remote sensing techniques are not well utilized at present, partly because of the lack of data and the required display/analysis facilities. The few data that are available suggest that combined use of such techniques can greatly facilitate investigation of frontal structure variability on both the fine scale and the mesoscale. *Figure* 4 illustrates one such technique with visible (color) data from an area south of Georges Bank. The frontal features on the lineal front across the center of the scenes are observed to be displaced between successive scenes. Such displacements in ocean color can be interpreted as tracers of the horizontal flow field near the front. An unanswered question is whether the "motions" observed arise from advection, or from propagation of wavelike phenomena along the front. In either case we observe characteristics on time and space scales which are related to the frontal variability. These are very difficult to measure in any other way. *Figure 5* is a composite of frontal outlines digitized from the scenes in *Figure 4*. Displacements in both the front delineating the eddy (a warm-core ring) and the front near the 200 m isobath can be noted. The eastward displacement of disturbances in the shelf break front is consistent with anticyclonic circulation of water about the warm-core ring. Ring streamers show similar behavior. The temporal variability seen in the ring frontal locus is interpretable as arising from rotation of the two-dimensional horizontal modal structure or as an alternating growth and decay. Other ring observations indicate that rotary motion is the correct interpretation. Consequently, using the color imagery, we can diagnose ring horizontal modal structure and rotation rate.

A second example, from the Somali Current (shown in *Figure 6*) maps the evolution of a multiple separating coastal circulation into a single gyre system. The Somali Current is classically described as a low-latitude equator-crossing western boundary current which joins with a large eddy ("Great Whirl"), separates from the East African Coast (10° - 12°N), and flows into the western Arabian Sea. *Figure 6* illustrates the evolution of associated frontal structures for 1976 through 1979 as observed by satellite. The classical description is found to be applicable only in the later stages of the Indian Monsoon, while a multiple frontal separation is more often found early in the Indian Monsoon. Frontal translation rates range from 5 to 150 $cm^{-1}$ over extents greater than 300 km. Such large-scale frontal variability cannot be observed from ships, and in fact was unknown until observed by satellite. These two examples illustrate two very different cases where satellite observation can make a significant input into our understanding of oceanic processes.

Infrared and other emission-based thermal monitoring systems view a very thin layer on the ocean surface (~1 mm). Color scanners, on the other hand, sense to tens of meters into the water column. Both methods can be used independently to study frontal variability; however, little has been done to study differences in simultaneous observations made with the two methods; work (Mueller and LaViolette, 1981) on Grand Banks has shown strikingly different frontal patterns in the thermal and color scenes. It is suspected that it will be the subtle differences in structure functions observed in such multispectral measurements that

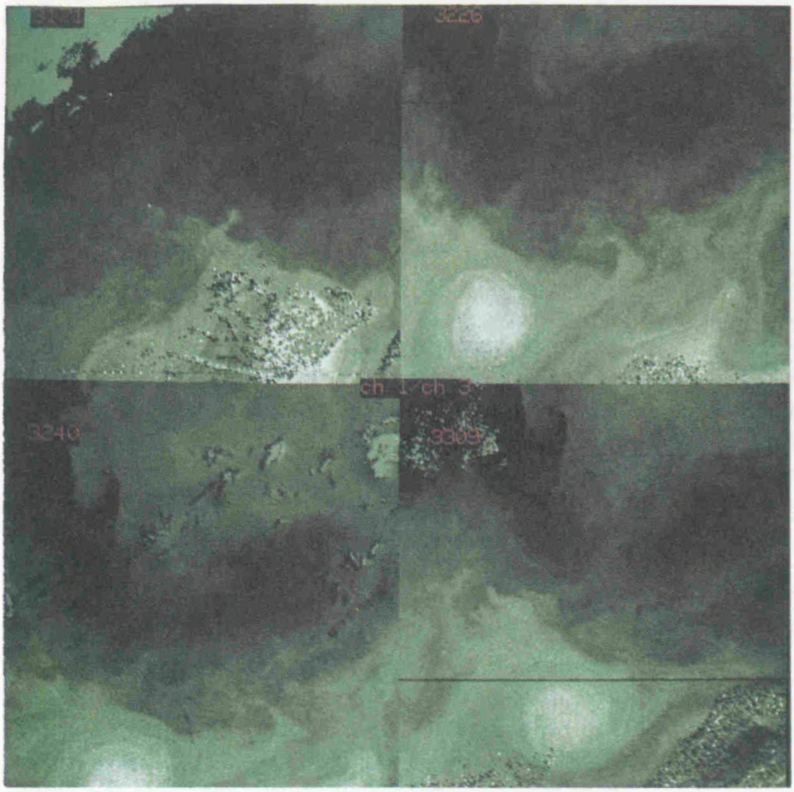



*Figure 4.* An area south of Georges Bank, as seen by the Coastal Zone Color Scanner on Nimbus 7. Successive scenes show the displacement of an ocean front, illustrating how the CZCS information can be used to trace horizontal flow fields.

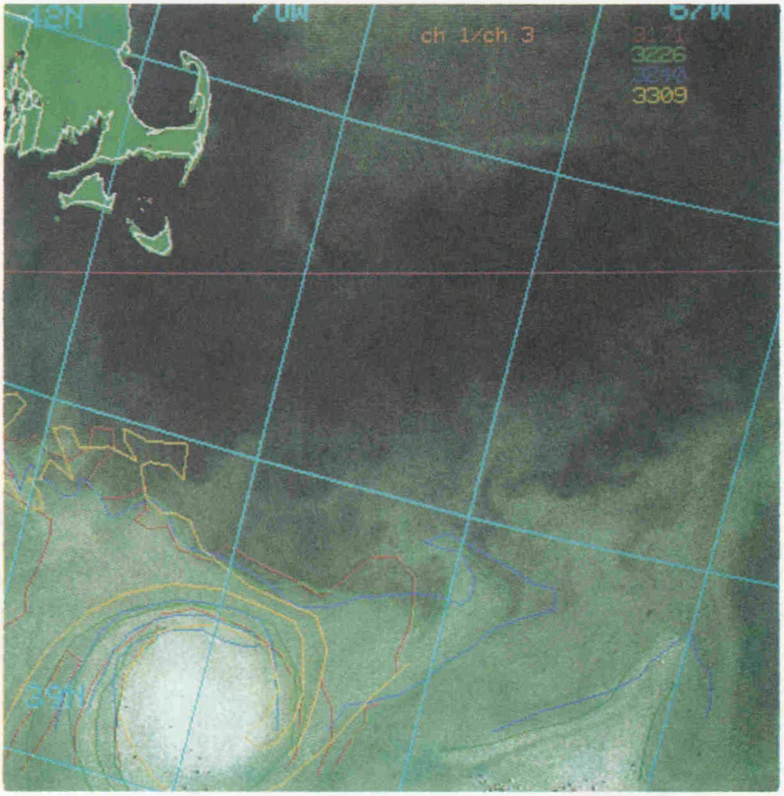
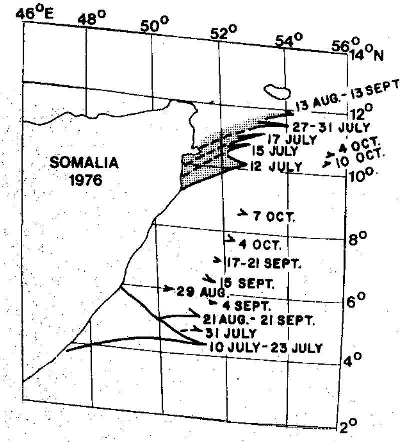



*Figure 5.* A composite of the frontal positions digitized from the scenes depicted in *Figure 4.* A warm-core ring and the front near the 200 m isobath are seen. (red-3171; green-3226; blue-3240; yellow-3309)



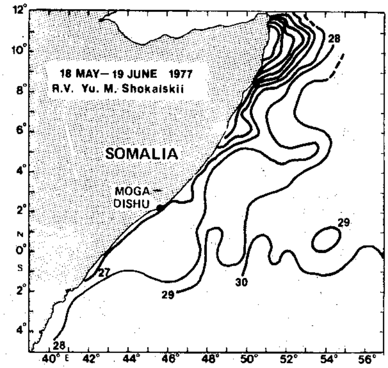
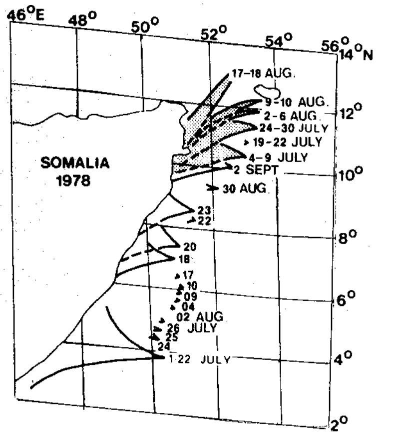




*Figure 6a.* Time sequence of satellite-observed frontal locations for northern and southern frontal wedges for year 1976. (Northern wedge hatched).

*Figure 6b.* Surface temperature map derived from measurements made onboard the R.V. SHOKALS'KII during May and June, 1977 off Somalia.



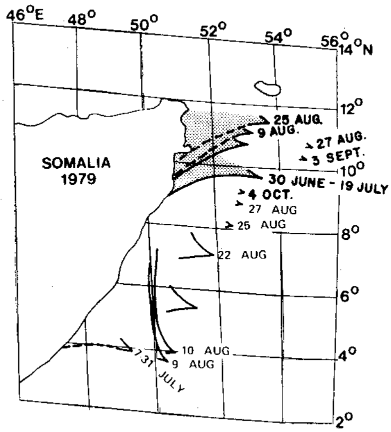




*Figure 6c.* Time sequence of satellite-observed frontal locations for northern and southern frontal wedges for year 1978. (Northern wedge hatched).

*Figure 6d.* Time sequence of satellite-observed frontal locations for northern and southern frontal wedges for year 1979. (Northern wedge hatched).

will lead to advances in fundamental understanding of phytoplankton dynamics, conservative properties of ocean color as a tracer, and decoupling scales for surface temperature fields from local variability. Optimally, but perhaps not realistically, future satellite systems for these kinds of investigations should include infrared and active and passive microwave observations to realize the full capability of the color scanner instrument.

#### 2.2.4.3 Sea-surface temperature

The color scanner is probably not a primary instrument for sea-surface-temperature observations, but it can contribute some information that might be useful. In fact, the reverse is true, as discussed elsewhere. The provision of accurate, coregistered temperature observations from another instrument on the same satellite would assist materially in the interpretation of the biological variability as seen by the scanner.

#### 2.2.4.4 Aerosols

Aside from obvious cloud effects, the corrections made to the green-band image arise largely from aerosol scattering and to a smaller extent to water vapor. The band in the far red (about 900 nanometers) offers an indirect clue as to scattering by atmospheric components; in a very clear atmosphere this image should be black, since the water surface is black at these frequencies. The blue-band image is a direct indication of aerosol scattering. Experimental data processing has shown that useful "images" of aerosol can be obtained, which possibly allow a good estimate of aerosol loading. As mentioned later, one person's "noise" is another person's "signal."

### 2.2.5 Images from Synthetic Aperture Radar (SAR)

The NOSS Science Working Group has not discussed these applications in detail since SAR was not included in the NOSS configuration, but there are detailed discussions elsewhere (e.g., Beal, DeLeonebros, and Katz, 1981). However, a few points are in order here in view of the broad nature of this document. SAR imagery from Seasat demonstrated that the images can provide important information on many oceanic features. Internal waves, for example, are well depicted. These features are useful to map, as they give clues on dynamic and mixing processes within the body of the ocean not otherwise easily discernible. In addition, neglect of the presence of internal waves, for example, could cause problems of interpretation of some observational fields owing to possible contamination of the desired signal by the superposed effects of the waves. Analysis of extensive subsurface buoy drifter motion fields or of acoustic sounding of the upper layer, for example, may be usefully supplemented by knowledge of the internal wave structures present. In addition, SAR observations give information on the surface wave spectrum, which could provide valuable ancillary information to aid in interpretation of such observations of such variables as wind and sea-surface temperature.

High-resolution SAR observations can be applied to studies of surface current and density structure which would be inferred from observations of shear instability and internal wave packet spacing. Ocean current systems of interest are widespread; some possible applications are the East Greenland Current, Antarctic Circumpolar Current, Kuroshio Current, Falkland Current, the Arctic Ocean in general, and the Ligurean Sea at some times of the year. Resolution greater than 1 km is required, and the images need to be archived in a form in which they would be readily accessible.

SAR images are well correlated with bottom topography down to water depths of 30 to 40 m, which provides a useful means to chart remote areas and to monitor changes.

If SAR instruments are flown for such purposes as ice monitoring and research, or for land surface observations, oceanic advantage of this valuable information would also be realized.

### 2.2.6 Data Collection and Location Systems (DCLS)

As already indicated, direct measurements will remain a central part of oceanography. Of particular importance for large-scale physical studies will be the heat storage in the upper few hundred meters and velocity measurements from both surface and subsurface floats. As mentioned earlier, extensive observations of sea-surface temperature and wind stress will also be needed in connection with remotely sensed systems. Observations are also required of air-sea-temperature differences and the humidity in the lowest layer to estimate the fluxes of sensible and latent heat through the surface.

A DCLS (Argos) was implemented on the NOAA operational satellites for the Global Weather Experiment, 1979, in cooperation with French colleagues who supplied the hardware and undertook the data processing. This joint arrangement is expected to continue through at least the mid–1980s. It must be remembered that the Argos system was designed primarily to track constant-level balloons accurately for the Global Weather Experiment, 1979; its applicability to other moving platforms was a most useful bonus, but the Argos system has some limitations with respect to other platforms that make it desirable to consider what improvements might increase its support to ocean sciences direct and remote sensing programs. For example, the DCLS for ocean sciences must be able to view a larger number of platforms than Argos does, up to several hundred platforms simultaneously, or else some regional projects being considered will not be able to use sufficient numbers of observing sites. The data rate should be increased, but not at the price of more power, so that considerable stored data can be relayed over one pass. Finally, it would be most useful for extensive oceanographic observations if the DCLS design could permit a relatively simple and inexpensive electronic package on the platform, to reduce the unit cost and thus encourage use of larger numbers of observing platforms.

The additional advantage of using a dedicated DCLS for ocean research projects is that the DCLS could then be on the same satellite as the remote sensing observing systems, and the direct observations would be related in space and time as closely as possible to the observations taken in the satellite field of view. Seasat and Nimbus 7 experiences have shown that such a close relationship would greatly simplify the data processing as well as reduce the natural discrepancies (arising through high-frequency variability) between the control/validation observations and the satellite observations.

Underwater telemetry can usually be accomplished by relatively low-power acoustic transmission, but long ranges impose severe constraints on batteries, weight, and overall system lifetime. Staging to satellites through a surface intermediary at a known location is an attractive alternative to present techniques, but only provided that a reliable and available satellite link is assured for the foreseeable future, with appropriate prospects for development in certain directions to be discussed later.

A somewhat different concept is the pop-up float, which rises to the surface for location by a satellite after a preset time at depth, and either cycles again or is discarded. This would be an attractive method of studying the longer-time-averaged currents. The unit cost of the float transmitter to the satellite should be low enough that large numbers of floats can be used.

## 2.3 Some Specific Problems to Be Addressed through Satellite Techniques

Described below is a variety of problems that satellite-based techniques can support, including the use of satellites as communication channels for the relay of data from remote fixed or drifting observational platforms (e.g., via the DCLS).

### 2.3.1 Subduction Along the Gulf Stream North Wall

As the Gulf Stream moves eastward away from Cape Hatteras, it appears to produce interaction with shelf waters to the north of its dynamic edge. These waters appear to be drawn eastward, under the Gulf Stream as it rides over them. Thermal infrared and, possibly, visible imagery would be useful to gain a better synoptic understanding of such processes and to correlate with direct data. Simultaneous definition of the dynamic edge of the Gulf Stream using radar altimeter data could provide an important clue to the physics involved. Finally, wind stress and some understanding of how it contributes to the process would be an important input required to complete the picture.

### 2.3.2 Mesoscale Eddy Research

Gulf Stream rings and meanders are the strongest known mesoscale eddy signals. Their influence upon the rest of the ocean is possibly quite large. Other mesoscale activity may be induced by wave propagation effects. Transports of salt, heat, and vorticity may be affected. The physical, chemical, and biological contrasts across a ring or meander are substantial and offer very favorable conditions for remote sensing. These features seem to be ideal sites for remote sensing of various quantities: surface temperature, elevation, chlorophyll content, and winds.

Significant scientific use of satellite data should go hand in hand with fundamental research into the dynamics of the mixed layer. We need to improve understanding of how the surface reflects the properties of the mixed layer and how the interaction of the mixed layer and the deeper flows shapes the evolution of these properties. Models have been used to examine interactions between the mixed layer and eddies, but further development is needed with more realistic models. Clearly we need to understand the role of advection in the interaction, the processes which occur when a deep front intersects the surface layer, and the feedback from the surface layer to the deep water. These theoretical problems need advancement along with instrument development.

### 2.3.3 Western Atlantic Shelf-Slope Oceanography, and Relations to the Gulf Stream Warm-Core Rings

Since 1974, thermal infrared data from the National Oceanic and Atmospheric Administration (NOAA) environmental satellites have been a principal basis for research in the Atlantic Environmental Group, National Marine Fisheries Service, on variation in physical environmental conditions in the waters of the continental shelf and slope fishing grounds off the northeast coast of the United States. Frontal analysis charts derived from infrared imagery, as well as the imagery itself, have been used for year-round analyses of the movements and perturbations of water mass boundaries. Such analyses have been published each year, describing the movements of the shelf-slope water front and the formations, movement, and ultimate destruction of Gulf Stream warm-core rings, which occur in the deep water between the stream and the continental slope. Variation in the position of the shelf-slope water front has been marked, especially in the spring of 1978, when the limit of shelf water was twice as far offshore as had been recorded before or has been since. Rapid advection of shelf water into the region off Nova Scotia was the evident cause of the phenomena.

Integration of water column data from ships of opportunity with the remote sensing data has provided information on the influence of the rings on water mass exchange across the shelf-slope front. Offshore entrainment of shelf water into the warmer, more saline slope water has been characteristically visible at the sea surface in satellite imagery; whereas intrusions of slope water and ring water onto the shelf have been largely restricted to the subsurface. Furthermore, each of these exchange processes is sometimes amplified by interaction between rings and Gulf Stream meanders. In oceanographic terms, the warm-core rings are a mechanism which transfers Gulf Stream water and energy shoreward into the proximity of the continental slope and outer shelf. Exchanges of water across the shelf-slope front are, in part, a function of this transfer.

Research is now in progress on changes in the position and flow pattern of the Gulf Stream and on cross correlation of the movements of the different fronts. Several considerations bear on plans for continuation and expansion of biological oceanographic research with remote sensing data:

- In recent years, satellites have provided the first source of fairly regular synoptic data on what may be called the "oceanic influence" on hydrodynamics in the shelf and slope regions. Routine data have been available for many years on other forcing functions such as surface wind stress, air temperature, coastal runoff, and long-term periodicities in the strength of tidal currents.

- Because of the short period of the satellite data base, the significance of annual and seasonal differences in the "oceanic influence," determined from these data, cannot be satisfactorily evaluated yet. Other data bases, such as hydrological data, are also very short of meeting requirements.

- Despite the demonstrated annual and seasonal differences in the prevalence of warm-core rings, the importance of their effect on cross-frontal exchange will not be known until completion of ship-board investigations of volume transports. Such investigations will be initiated in the fall of 1981 by oceanographers from several institutions (with NSF funding).

- New technology in satellite remote sensing may improve the quality of the ongoing research. The color scanner, for example, reveals spatial and temporal patterns even when surface thermal contrasts are lacking. Also, radar altimeters and other microwave instrumentation on satellites permit "all-weather" detection of water mass boundaries at the surface.

- New satellite technology can also permit new lines of fishery oceanographic research. For example, the color scanner data, if available routinely, will reveal the spatial and temporal patterns of primary biological productivity on the outer continental shelf, and indicate the importance of nutrient enrichment resulting from upwelling of deep slope water.
- The region off the northeast coast is one of the most favorable in the world ocean for satellite oceanography because of the energetic circulation and consequent strong differences in properties between water masses. For this reason, water mass boundaries tend to be visible from satellites even when atmospheric transparency is reduced.

### 2.3.4 World Ocean Exploration with Drifters (WOED)

The practicability of large-scale deployment and the scientific utility of drifting buoys was demonstrated in the Global Weather Experiment (GWE), 1979. The buoy program for the GWE was invented and implemented for meteorological purposes. The data fields, however, as shown in *Figure* 7, are also useful *per se* to define some of the oceanic circulation. The success of the program has stimulated new technical efforts to develop drifters of several types into instruments of broader oceanographic use—better sensors, reliable thermister chains to obtain temperature profiles, subsurface flotation with tracking and data relay via the sound channel, or via a pop-up technique and satellite data relay, etc.

An exciting research prospect, feasible in the second half of the 1980s, is exploration of ocean circulation on a global basis using drifters both as tracers of horizontal advection and as platforms from which scalar properties are measured. The objective of this exploration would be development of worldwide maps of statistical indicators of the general circulation, such as mean flow, eddy energy, and Reynolds stress, and of lateral mixing as indicated by drifter dispersion. Eventually, it will be necessary to map variability in various frequency bands at various depths on a global basis. Nearly continuous satellite positioning and data telemetry permit intensive measurement of the upper ocean on a global basis at a reasonable level of effort. Present methods of communicating with drifters at depth are more costly than is ultimately desirable. This will probably limit the use of very frequently positioned subsurface drifters to regional studies in the near future. However, for describing

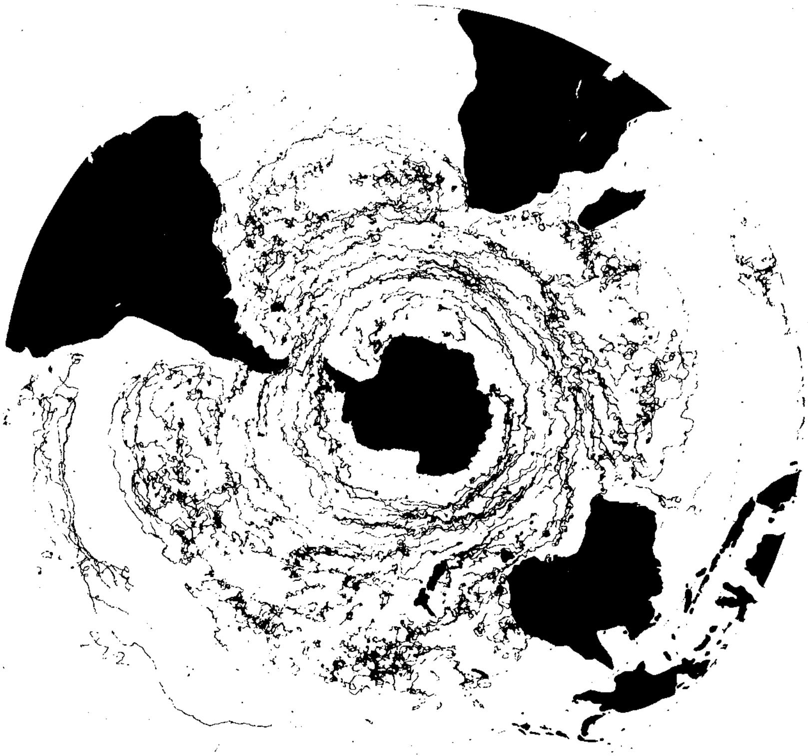


*Figure 7.* Composite of drifting buoy tracks during the Global Weather Experiment, 1979. Some 300 buoys were deployed in 1978 and 1979 to maintain a network of stations in the Southern Ocean for observing surface pressure and temperature. In addition, the drift patterns provide valuable insight into oceanic circulation characteristics.

the mean general circulation, including lateral eddy dispersion, the use of satellite-positioned pop-up drifters may permit global coverage at a reasonable level of effort.

The efficiency of pop-up drifters arises from low unit cost and the fact that the initial and final drifter positions for a deployment of months yield an integral of velocity more representative of the mean general circulation than individual velocity measurements are. For example, accurate determination of the mean velocity requires removing sampling errors associated with eddies and this requires knowledge of the average of observed velocity over long times. The measurement error is roughly proportional to record length to the minus one-half power and, for Mid-Ocean Dynamics Experiment (MODE) eddy scales, about five years of data are required to achieve an oceanographically significant accuracy of 3 mm/s. Since system accuracy is dependent mainly on the total measurement time, it is clearly efficient to take advantage of the natural integration associated with pop-up drifters. Similar criteria apply for measuring lateral dispersion (or eddy diffusivity, in cases where the notion applies), and end-point drifters are again efficient tools.

Essential to the pop-up drifter concept is availability of inexpensive floats which, in turn, depends on availability of satellite tracking which permits inexpensive equipment in the drifter. At the same time, accuracy requirements are an order of magnitude less stringent than that available from the Argos system. Cost is a critical factor because large numbers of floats will be required to map several levels of the global ocean. For example, using the MODE-derived estimates of dispersion, two-year deployments produce statistical characteristics of regions approximately 200 km on a side, and three floats in each region are required to establish the mean velocity to within 3 mm/s. If it is assumed that regions requiring greater resolution and accuracy are balanced by regions where lower resolution and/or accuracy will suffice, it seems that $10^3$ floats might produce a quite useful global map at one depth and something like $10^4$ might be used over a decade in mapping out various levels, exploring year-to-year variability, and filling in holes found in the deployment array.

Assuming that buoy development will proceed as planned (a substantial project is now under way that is supported by NASA and NOAA and that involves collaboration by a group of researchers as well as sensor and buoy engineers) and assuming that a suitable DCLS is available, a substantial program would be feasible to produce worldwide maps of statistics of ocean circulation for four frequency bands: band (i), one cycle per two to 40 days, which is a spectral band containing the results of direct atmospheric forcing; band (ii), one cycle per 40-150 days, the temporal mesoscale; band (iii), one cycle per 150 days to the length of a feasible program, say three to five years, which contains the secular climatic variability scale; and band (iv), the long-term mean, representative of the general circulation. All buoys would include sensors for temperature and pressure, and surface drifters would profile down to 100-200 m. Drifters would be distributed at the surface, in the thermocline, and at an abyssal level, say 3,000-4,000 m. Satellite DCLS or acoustic relay, or a combination, would be used.

- ***Superdrifter:*** If a drifter, equipped with a 100-200 m thermister chain, could also be equipped with a Doppler logging device to obtain current profiles down to 100-200 m, then substantial improvement could be made on observations necessary to develop further models of ocean response to the atmosphere and to validate their performance. Associated field programs could be envisioned also. The superdrifter would provide valuable information in frequency band (i), and there may also be some linkage in the air-sea interaction aspects in bands (ii) and (iii).

- *Pop-up drifters:* Pop-up drifters would be crucial where advection is slow and at depths and locations where acoustic tracking is not practical. The drifters must be inexpensive and reliable; the associated satellite DCLS must have a wide frequency acceptance band, since there will be a signficant temperature change as the pop-ups surface, and it would not be practical to include a highly regulated or stable oscillator on them.

*The WOED effort should probably be built up through regional studies, and close coordination should be included with altimeter flights (TOPEX) and with scatterometer observations. It might also be useful, in light of the discussion earlier, to try to coordinate extensive drifter experiments with the operation of a color scanner, since the scanner images may also contain valuable information on movement of surface structures.*

### 2.3.5 Remote Sensing of the Heat Budget of the Ocean

This discussion is closely related to several other sections, particularly the following one.

Ocean circulation is strongly affected by atmospheric winds and the spatially varying net radiant heating and sensible and latent cooling of the ocean surface, while the ocean influences atmospheric circulation through the transfer of heat and moisture to the lower layers of the atmosphere. Because the ocean flow and ocean diffusion transport heat from one place to another, the thermal energy which the ocean might absorb in one place might be given back to the atmosphere at a very different place and at a different time. The ocean's capacity to store thermal energy for long periods and move it around over large areas can result in slow changes of atmospheric circulation patterns or in climate changes. The determination of the oceanic heat budget and the dynamical processes which change it is paramount to understanding and modeling climate changes over large areas of the globe.

Remote ocean sensing can play an important part in measuring the air-sea exchange process over large areas of the open ocean. For example, climatologists have shown that slowly varying ocean surface temperature patterns, and the implied heat exchange patterns, in the equatorial and southern Pacific are directly related to winter climate patterns over North America. But this ocean area is not crossed by ships on a regular basis and to study the role of the ocean in this "southern oscillation," remote sensing is imperative. In the next decade, oceanographers plan to measure the equatorial and southern Pacific Ocean heat absorption, its vertical mixing through the upper layer, its advection, and its transfer back to the atmosphere. First, we discuss what measurements are needed and then we show why and how we need the data acquired through satellites.

Near the ocean surface, the Pacific equatorial and subtropical southern Pacific circulations compose a single, large, anticlockwise cell. It consists of a broad, slow (10 cm/s) flow to the east between 20°S and 30°S; it turns increasingly north, east of 110°W, and flows westward as a powerful surface current (50 cm/s) along the entire equatorial belt from the Galapagos Islands to Mindanao. At a hundred meters below the surface and a few hundred kilometers on either side of the equator, colder water from the undercurrent is thought to well up into the surface layers (about 1 or 2 m/day) and it is thought to be sinking (about 1 or 2 cm/day) over the remainder of this gyre. This pattern is maintained by atmospheric forcing, but because it lies under the slowly oscillating southern hemispheric atmosphere, slow changes should also occur in the ocean. Slow changes are known to exist in the sea-surface temperature. These show that beginning in the summer the ocean appears to transport large pools of warm water in the powerful surface flow from the west coast of South America to the central equatorial Pacific. There, two seasons later in winter, the anomalously warm water gives its excess heat back to the atmosphere and produces significant changes of the North American winter climate.

*How and where is this warm water pool formed at depth? Is it destroyed by cold equatorial upwelling and subsequent vertical mixing or does the atmosphere destroy it by latent cooling? What is the transport rate of heat to the north, across the northern edge of this circulation cell? Does the entire South Pacific circulation cell oscillate in response to the southern atmospheric oscillation; is this oscillation intensified at the equator or is the change in the surface circulation pattern produced entirely by trapped equatorial phenomena? To answer these questions, accurate observations are needed of the heat exchange rate between the ocean and atmosphere, the circulation rate of water and the vertical (and horizontal) mixing rate in the upper ocean.*

One observational program, planned to occur from 1983 to 1990, is to measure directly the largest elements of the momentum and heat budget in the central eastern equatorial ocean, where the anomalous heating of the atmosphere occurs by the latent cooling of the ocean. The circulation can be measured with arrays of internally recording current meters and surface and subsurface drifters which report their position via satellite. Important here is the development of inexpensive, new pop-up floats by which the equatorial convergence of water and upwelling can be measured. Their position upon release and resurfacing will be determined by satellite. Drifters which are accurately calibrated to follow water parcels at various levels and which report positions continuously should also be developed. In this experiment, the stress is on accurate measurements of horizontal velocity because the budgets of mass, momentum, and vorticity can then be estimated accurately. Plans are to maintain 50-200 velocity drifters for five years at the equatorial zone, ± 5°N, 90°W-180°W. Current-meter arrays will be less extensive, but have a similar deployment schedule.

The study of the heat budget requires measurements of water velocity, the subsurface temperature profile, and the air-sea heat exchange rate. First, this can be done in small areas with current-meter arrays. Second, arrays of floating or moored thermistor string buoys and ships of opportunity, and expendable bathythermograph (XBT) sections can be used to measure the heat content change over a larger volume. Sufficient accuracy exists in present instruments. Again, the thermistor buoy data will be relayed by satellite. For this purpose, each buoy will have ten to 12 thermistors and three to four pressure gauges; 30-50 buoys will be maintained over a seven-year period. New developments for the thermistor buoys are needed for air temperature sensors, humidity sensors, and wind speed sensors so that the latent heat release from the ocean can be computed. Meteorological data from merchant ships will complement the air-sea buoy data.

Aside from the data transfer facility in this experiment, the important role of the satellite is in the measurement of the large-spatial-scale surface wind stress, the ocean surface radiation budget (short-wave incident minus the long-wave back radiation, $\lesssim$20 W/m$^2$), cloud cover, and brightness. New developments, or algorithms, are needed for a more accurate determination of the equatorial relative sea-surface temperature ($\lesssim$0.5°C *relative* accuracy) and moisture content of the low-level atmosphere. The satellite sea-surface-temperature pattern will be used to fill in the field *between* the buoy and ship measurements. If rainfall rate can also be measured remotely, it will be useful, for it is an important flux in the upper ocean density budget.

***In summary, satellite systems are needed for inexpensive and voluminous data transmission and for surface location, surface radiation budget, wind stress, relative sea-surface temperature, and atmospheric cloud and moisture content. Without these facilities and sensors, accurate observations of the equatorial upper ocean heat and momentum budgets cannot be made. With these observations, however, oceanographers can design and carry out a new generation of accurate large-scale experiments.***

Because ocean circulation is continuous, equatorial ocean phenomena are not isolated from the larger-scale South Pacific influence. The South Pacific subtropical circulation, though important to the world climate, is not understood because it is in a very remote area. In the next decade, physical oceanographers plan to begin more intense, direct descriptive study of the South Pacific circulation.

*Here, data from existing satellite systems and new satellite systems to be flown in the future can really lead the way. Very basic information is needed: What are the space and time scales of the sea-surface-temperature patterns in the South Pacific? What are the space and time scales of the atmospheric wind field as determined from cloud motions, and how are these related to the surface wind? If an accurate altimeter experiment is flown, the pan-Pacific time fluctuations of sea level can be measured (~2 cm relative accuracy would be sufficient) over areas where no island stations exist. The radiation budget of the ocean surface can be estimated, which will allow oceanographers to design a corresponding program to measure the subsurface storage and to estimate latent and sensible heat flux. Simple, descriptive, remote oceanography from space will have the largest impact on science in areas where oceanographers have* not *gone with ships; the subtropical South Pacific is an important area for such investigation.*

### 2.3.6 Heat Budget Studies of the Ocean-Atmosphere Interface

As outlined above, the oceanic heat budget is a very important quantity, and is related to the ocean-atmosphere interface. A key element in the study of the interactions between the oceans and the atmosphere is the heat budget at the interface. Not only does it provide a quantitative estimation of the heat exchanged between the oceans and the atmosphere, but it also is an important component of the upper ocean heat budget.

For quantitative climate studies, such as modeling of the climate system or sensitivity studies, the heat budget at the interface needs to be known with a 10-15 $W/m^2$ accuracy on space scales of several hundreds to thousands of kilometers, and time scales of a few weeks or longer. However, useful qualitative information can be obtained from less accurate estimates presented in the form of indices, for instance. A large part of our present knowledge is, in fact, based on this type of information.

The heat budget at the ocean-atmosphere interface is determined by the net radiative budget and the heat fluxes (latent and sensible). In the tropical regions two dominant terms are the incoming solar radiation (insolation) and the latent heat flux. The insolation can be derived from satellite measurements—measurements from a microwave radiometer and scatterometer can be interpreted in terms of quantities which are elements of the heat fluxes (i.e., the water-vapor content in the lower layer, and surface wind). The addition of ancillary information from other satellites or direct observations would allow improvement and closure of the budget. The combination of data from various sources and the redefinition of the microwave measurements in terms of heat budget parameters would be facilitated by the availability of extensive processing and data merging capability.

### 2.3.6.1 Present status

New approaches are presently being formulated for estimating the heat budget at the interface by combining integrating existing data both from satellite and from instruments *in situ*. A review of their status and potential is outlined, starting with the two main components, i.e., net radiative budget and heat fluxes, and then looking more specifically at major components entering into the determination of the heat fluxes.

#### 2.3.6.1.1 Net radiative budget

The net radiative budget is an important term in the heat budget, particularly in the tropics, where most of the heat acquired by the ocean comes from the absorption of solar radiation by the surface layers. The variability of the incoming solar radiation (insolation), mostly resulting from cloud variability, can be adequately monitored from satellites.

- *Insolation shortwave budget.* Daily estimates from geostationary satellite data for limited areas are close to 15 $W/m^2$ accuracy over very small scales (10-20 km). Estimation for larger areas would undoubtedly reach that accuracy, and the implementation of the appropriate methodology for large-scale problems is presently being tested. Long series of calibrated geostationary satellite data, however, are not available, and therefore alternative approaches using data from polar-orbiting satellites must be devised in order to obtain at least a climatological index for past insolation.

- *Longwave budget.* No methodology is available from satellites yet. Present knowledge relies on parameterization as a function of visually estimated cloud cover and sea-surface temperature. In the tropics it is a small term (results from the GARP Atlantic Tropical Experiment, 1974); its magnitude could be derived from simple parameterization of cloud effects on calculated upwelling longwave radiation. At higher latitudes it is more important, but the prospects are dimmer since it depends on cloud base temperature, a quantity which is difficult to estimate from satellites.

#### 2.3.6.1.2 Heat flux (latent and sensible)

A complete description of the heat budget requires quantitative estimates of the latent and sensible heat fluxes. Although the quantities needed for these estimates (air-sea temperature difference and boundary layer humidities) cannot be measured directly, they may perhaps be inferred from microwave radiometer and scatterometer measurements, if these data are interpreted and processed appropriately. Three approaches presently seem promising for quantitative evaluation of the total flux:

- Determining heat flux and evaporation information from combined satellite data, ship reports, and weather buoys using bulk aerodynamic formulas. More work is required in order to discriminate between parameterizations and also in order to optimize the combination procedure.
- Inferring evaporation, as a residual, from the total water budget (estimated from microwave radiometer measurements) and the wind field.
- Determining fluxes using atmospheric boundary layer similarity formulas developed for vertically integrated temperature and humidity profiles (which can be derived from other satellite measurements).

The latent heat flux should be studied first since it is the larger of the two, particularly in the tropical regions.

Qualitative information on flux can also be obtained by monitoring changes in cloud patterns by measuring the length of clear fetch, the space between cloud streets, or the size of convective cells. Strong heat flux event records could also be compiled using satellite visible and infrared images.

Two major components are part of the data base required for heat budget studies at the ocean-atmosphere interface: the sea-surface temperature and the surface wind field. Both enter in all the heat flux determinations and, in addition, they are crucial to any evaluation of the flux estimation from satellites.

Small sea-surface-temperature changes in the tropical regions seem to be associated with the intensity of some seasonal or interannual atmospheric phenomena, through ocean-atmosphere interaction processes (Indian Monsoon, continental U.S.A. weather, etc.). The monitoring of these changes is difficult from scarce measurements by ships of opportunity; satellites offer better coverage but the accuracy of the sea-surface temperature routinely produced by the National Earth Satellite Service (NESS) has not been adequate for such small changes to be estimated correctly. New methodologies offer some improvements. For example, multichannel infrared window measurements by the Advanced Very High Resolution Radiometer (AVHRR) and Visible and Infrared Spin-Scan Radiometer Atmospheric Sounder (VAS), multichannel microwave measurements with the Scanning Multichannel Microwave Radiometer (SMMR), and the fast repetition rate provided by VAS on a geostationary satellite provide substantially improved accuracies for limited cases. Comparison studies just completed show significant improvement in temperature estimates. In addition, it is important to continue research on combining infrared and microwave sea-surface-temperature products to improve coverage and accuracy.

Surface winds over the vast expanse of tropical oceans between subtropical ridges are poorly observed as a result of the scarcity of ships (these areas are away from merchant ship routes) and island observations. The observations are insufficient not only for daily analyses but also for monthly means.

Current global operational analysis schemes which use satellite-observed cloud-drift winds to infer surface winds through parameterization of the boundary layer are unsuccessful, because wind fluctuations between the surface and the low-cloud level (1,000 m) are random and uncorrelated at high frequencies (daily time scale). However, at longer time scales, say ten days, the correlation becomes acceptable.

Data from a high-resolution microwave system and scatterometer offer the best hope for filling this data void. However, as with any new type of data, there would also have to be a dedicated program devoted to evaluation of the observations. The evaluation should be done for variable time scales, since the bulk of winds for comparison are observed at the 19 m level and there is no assurance of a definable relationship at high frequencies between the winds at 19 m and at the ocean-atmosphere interface.

Methods have been developed to use satellite cloud-drift winds to deduce winds at the surface. Preliminary tests show promising results in deriving monthly mean surface winds using mean climatological wind shear. Scatterometer winds from Seasat have raised considerable enthusiasm despite the directional ambiguity problem. Future scatterometers should be designed to remove this ambiguity, but additional evaluation will be required for final inclusion of the winds into flux estimations.

### 2.3.6.1.3 Additional elements

Water-vapor and rain-rate estimations also enter into the determination of the latent heat flux through latent heat storage in the atmosphere and conversion of latent heat to sensible heat in the atmosphere. Since they are used in residual approaches, their accuracy influences the error in the determination of the residuals. High-resolution microwave measurements should provide these two estimates relatively reliably. A high-quality rain-rate algorithm should also be developed.

#### 2.3.6.2 Ancillary measurements

Additional information is necessary for three main purposes:

- To close the heat budget in the case of the radiation measurements,
- To validate algorithms developed for improved accuracy,
- To combine with measurements from oceanographic satellites in the determination of the heat fluxes.

These data would mostly consist of:

- Data from operational satellites (GOES, TIROS, and NOAA Series) or research satellites (ERBE, Nimbus),
- Buoys and ship data relayed by a DCLS (Argos or equivalent): sea-surface temperature, air and dew point temperature, surface wind, and possibly some radiation information (from ship only),
- Operational products such as winds derived from cloud-drift measurements.

### 2.3.7 Ice Studies

Ice is not only an important constituent of the polar seas, *per se*, but the extensive polar ice formation also has high relevance to studies of climatic variability, as well as to practical matters such as navigation and offshore operations. Under the sponsorship of NASA, a group of ice experts produced a comprehensive report, ***ICEX: Ice and Climate Experiment*** (December 1979, NASA), which discusses in elegant detail the many challenges of ice studies and the relationships to climatic and oceanic processes. Among the subjects discussed are navigation in the northern oceans, the generation of cold bottom water, interactions between the oceans and ice sheets, the possible instability of the West Antarctic Ice Sheet, and the control of the heat budget of the ice-covered oceans. A knowledge of ice concentrations, extent, and character (first year, multiyear) is critical to many fundamental ocean studies.

Ice is readily observable through cloud cover using passive or active microwave systems. A considerable amount of information has been gained from microwave instruments on research and operational polar-orbiting satellites, and the SAR flown on Seasat has demonstrated the power of this instrument to provide important details of sea ice structures. Operational passive microwave systems will continue to be flown and will continue to provide monitoring capability of some of the important ice variables. If SAR and/or high-resolution passive systems are flown in the future, they will provide additional important ice information.

Satellite radar altimeters, as demonstrated using the observations from GEOS 3, can be used to measure topographic changes in the great continental ice sheets of Greenland and Antarctica with accuracies an order of magnitude greater than land-based or aircraft surveys. The ICEX document should be referred to for the many details of ice studies relevant to oceanic research. In addition, some new programs are being developed for the study of ice-ocean interactions, such as the Marginal Ice Zone Experiment (MIZEX), for which satellite observations will be needed.

In addition to the seven examples discussed above, the international community is discussing, in the context of the World Climate Research Program, three possible major international activities. These are discussed below, briefly, highlighting the contributions proposed from satellite-based observing systems. It will be seen that these three proposed experiments have close relations to several of the experiments discussed above.

**2.3.8 Cage** (refers to the configuration of the observing network)

Cage is a proposed experiment which would focus on determining the heat fluxes in and above the North Atlantic and the major mechanisms for such fluxes, and on intercomparing various methodologies for estimating heat flux through the ocean surface, within the water column, and within the atmosphere. Cage is under discussion as a major oceanographic contribution to the World Climate Research Program. Possible contributions from satellites and satellite-based systems include:

- A large number of floats at a constant depth in the abyssal water to determine a broad-scale reference level velocity field (outside the western boundary current) and barotropic eddy statistics. Satellite tracking and data relay would be an essential part of such an effort.
- A TOPEX program at the time of Cage would contribute exceptionally important observations on ocean circulation. A scatterometer flight during this period would also contribute exceptionally useful wind information. As far as it is known at this time, Cage is not being planned around such satellite efforts explicitly; rather, it is being planned to be able to attain its scientific goals relatively independently of specific satellite flight, and to rely heavily on direct observational techniques. Satellite efforts of the kind mentioned here, however, would constitute quite significant additional information, and the Cage effort itself would be a unique context, for comparison purposes, in which to analyze the satellite observations.
- Ships of opportunity supplemented by drifting buoys to determine the annual average fluxes of sensible and latent heat across the sur-

face, the Ekman heat flux, and estimates of cloudiness for estimates of net radiation (data relay via satellites would facilitate the data collection).

- The operational meteorological network to determine the annual average atmospheric horizontal flux divergence of sensible and latent heat by use of satellite techniques. Some special efforts along the southern boundary (e.g., tropical Atlantic or Pacific) would be needed, as in the kind of ship/aircraft efforts deployed for the special observing periods of the Global Weather Experiment, 1979.
- Satellite observations of the net radiation at the top of the atmosphere (e.g., through ERBE follow-on observations).
- Verifying inferences of the three-dimensional velocity field from reference-level floats together with the large-scale density structure from additional floats at a number of levels, using a satellite DCLS.

Cage also supposes that contemporary instruments capable of monitoring the earth's radiation budget at the top of the atmosphere will be continued, as will the visible and infrared imager used for estimating the net radiation at the ocean surface.

### 2.3.9 The Global Ocean Circulation Experiment

The Global Ocean Circulation Experiment would focus on determining the broad-scale trajectories of water parcels in the world ocean, on the distribution of water mass properties and passive tracers, and on the identification of regions of significant water mass conversion resulting from vertical overturning or diffusive mixing.

A satellite-borne scatterometer and altimeter (e.g., TOPEX) measuring the surface stress and sea level relative to the geoid (to ± 2 cm) for three to five years would be a major observing element for this experiment.

### 2.3.10 A Tropical Experiment

A Tropical Experiment (most probably in the Pacific) would focus on the oceanic response to changes in atmospheric forcing on time scales of a few months to several years, in particular on determining the delayed influences on sea-surface temperature which then feed back into the atmospheric circulation for another cycle of the Southern Oscillation.

Satellite contributions would include:

- Space-based observations of wind stress, sea level (TOPEX to ± 5 cm relative to a fixed reference), and (if possible) sea-surface temperature for a minimum of five years.

- Extensive direct observations of the near surface layers from ships of opportunity and drifters to determine the heat storage, surface heat fluxes, and geostrophic velocities, as well as wind speed and sea-surface temperature.

After extensive intercomparison of directly obtained data with space-derived information, the latter would be used to validate numerical models of the time-dependent response of the ocean to the atmospheric forcing and could be evaluated for possible use in climate prediction and long-range monitoring. Sea level is needed here primarily as an indication of the depth of the thermocline, and is not used to infer the abyssal velocities. This allows less stringent accuracy requirements. Also of importance would be the information on the wind-forced convergence zones derived from altimeter observations. A supplementary study would investigate the dissipative processes contributing to the equilibrium of the equatorial undercurrent.

### 2.3.11 Ocean Sciences, Climate Studies, and Satellite Capabilities

The oceans are perhaps the dominant element of the atmosphere-ocean-land-cryosphere climatic system. Numerous studies in the last several decades have indicated the tantalizingly close and probably causal relation between large-scale changes in ocean thermal structure and concurrent changes in the major atmospheric flow fields. More recent results suggest that not only is the relationship concurrent, but there are significant lead and lag relationships between the two. In at least one case it has been possible to predict future atmospheric conditions from prior knowledge of ocean variables alone. Several complex scenarios have been developed to explain this predictive capability.

All of the cases where significant predictability has been found are associated with a phenomenon that meteorologists term the "Southern Oscillation" (hereafter abbreviated SO). Indeed, careful examination shows that many of the scientific papers written on climate variability in the last several decades deal with one or another manifestation of the SO. The name SO would lead one to believe this phenomenon is confined to the Southern Hemisphere. In fact, it is a global-scale phenomenon in which components of the atmosphere, ocean, and probably the cryosphere, fluctuate more or less together.

It seems clear that many scientists interested in climate will concentrate their activities on this particular signal over the next decade or so. This concentration will occur not only because of the potential predictive value of the SO phenomenon, but also because it is, in magnitude, the strongest "nonrandom" fluctuation that occurs on time scales one can reasonably expect to study. The following paragraphs provide more information on the SO, and indicate as well a set of scientific steps that will lead to a detailed SO field program toward the end of the decade. Satellite measurement capabilities will be critical to many aspects of the SO scientific program.

#### 2.3.11.1 Definition phase

If one asks, "What is the SO?" the answer generally comes back as something to the effect that it is the oscillation of the sea-level-pressure difference between the Indonesian region and the southeastern Pacific Ocean. This pressure fluctuation arises from a shifting of atmospheric mass between the Eastern and Western Hemispheres. Others view the phenomenon as an interaction between the Pacific trade wind fields and the monsoonal systems. In any event, none of these descriptions is really satisfactory for they only refer to indices of a process that has global ramifications.

*The first job for the climatologist, then, is to define adequately the global couplings in the ocean and atmosphere that attend the thing we now simply call the SO. We will have to answer such questions as: What fields and regions of the globe participate in the SO? What are the space and time scales of variability in these fields and how can we optimally measure SO phenomena? Why is it that many SO phenomena (e.g., El Niño) appear tightly locked to the seasonal cycle? In short, we will have to do a comprehensive, quantitative job of describing what we mean by the term SO. A strong start has been made in this direction. Additional field measurements (see below) will be required to complete the process.*

#### 2.3.11.2 Hypotheses

The description called for above should give rise to a series of hypotheses regarding the mechanisms associated with SO-type phenomena. For instance, numerous spectral analyses indicate that the SO phenomena most often lie in the frequency range between about one cycle per three years and one cycle per six years. We currently have no hypotheses to explain this range of preferred time scales. It does not appear possible that their origin is in the atmosphere, for the atmosphere's "memory" is simply too short. However, the ocean is an attractive candidate for these time scales since they are comparable with the circulation time around major ocean gyres.

If the oceans do play an important role in the SO, then we must be prepared to undertake a study of ocean heat budgets since it is the ocean-to-atmosphere heat flux that will influence the atmosphere and, perhaps, partially force the SO. This means we will need ways to estimate the air-sea heat exchange as well as the advection of heat by ocean currents.

### 2.3.11.3 Field programs; Phase I—definition

Almost all current knowledge about the SO comes from historical data measured at various land stations or islands or from ships. This type of historical data is and will continue to be a tremendous aid in conducting the "definition" stage indicated above. However, there are huge regions in the Southern Hemisphere, particularly the Southern Ocean, where there is no information: ships do not go there, there are no islands, etc. These areas, of necessity, will remain question marks in the definition phase. This will make it difficult to construct hypotheses regarding the SO. In fact, the SO appears to require an understanding of how the major atmospheric *fields* interact with each other and the ocean. From the oceanic point of view, we will have to understand the interaction of entire current systems. Field interactions of the type envisioned are not well described, in general, by a few spot measurements.

*It is clear that a study of the SO will require a near-global perspective. The only realistic way to obtain the type of information for this view is via satellite. However, the satellites themselves will not provide all the information we need. A strong requirement exists for complementary measurements from drifting buoys, instrumented islands, ship-of-opportunity programs, etc. In context then, the satellite data will provide the "glue" necessary to tie together current conventional measurements made on a sparse spatial grid. Satellite information will also help us understand how to interpret the (spot) historical record in terms of field properties.*

*In summary, a preliminary measurement program using both conventional and satellite systems is required to even delineate SO phenomena, particularly in the Southern Hemisphere. Climatologists are in a position now to begin to specify the required data to outline such a measurement program.*

### 2.3.11.4 Field programs; Phase II—process experiment

Given a reasonable set of SO hypotheses, plus an idea of the type of sampling scheme needed to resolve the SO signals, meteorologists and oceanographers will be able to design a reasonable field program to investigate the origin of the phenomenon. Such a program will be highly compatible with proposed large-scale oceanographic programs of the 1980s (e.g., the WOED discussed above) and with the instrument development required by these programs (e.g., drifting buoys, remote data transmission, etc.). The greatest potential for disagreement appears to be the siting of such experiments (e.g., tropical and South Pacific versus North Atlantic).

### 2.3.11.5 Data problem

A major difficulty associated with the SO project is the huge data management specter that it raises. The climatologists will have to find a method to easily synthesize disparate types of information from numerous sources. A giant stride towards this synthesis can be achieved by developing a data system that is common to as many sources as possible. In this case the role of the satellite again appears exceedingly important, for the satellite can act as a data link that will collect and relay both remotely sensed information and information from a variety of surface and subsurface platforms. Having many types of information in a single data stream greatly simplifies many of the coordination and collation problems that would otherwise arise.

### 2.3.11.6 The role of satellites

*The role of the satellite in future climatological research, such as the SO project, is twofold. First, it must provide estimates of remotely sensed* fields *that can be related to conventional historical measurements taken from platforms at sea or on land. Such variables include, but are not limited to, sea-surface temperature, wind velocity, total precipitable water, sea-level wind velocities, temperatures, etc. Much has been written about these measurement capabilities. In summary, prudent combination of conventional measurements with remotely sensed data now appears to offer a capability accurate enough to initate a SO experiment.*

*The second capability we need from the satellite is the ability to position and collect data from remote stations, e.g., drifting buoys, islands, ships of opportunity. This capability currently exists but has not been applied to the climatic experiment envisioned here.*

### 2.3.11.7 Special instrument problems

The study of climatic variability introduces a special problem both for conventional and, particularly, for satellite instrumentation. Relatively small amounts of instrument drift will, over a particular sensor's lifetime, look much like the signals that we expect to study.

*It is absolutely vital that instrument stability and long-term calibration be matters of key concern in any future conventional or satellite system that will be used for climate research. The stability and drift problem also suggests that the satellite products must constantly be referenced to conventional measurement sets with which we are familiar. We will be able to find regions of the ocean where the remotely sensed fields can be compared with conventional estimates of the fields. This field-field comparison may avoid the problem of trying to determine the representativeness of individual calibration sites.*

### 2.3.12 Biological Studies

The oceanic physical processes relate closely to many biological processes of importance. Some important applications of the color scanner observations have already been mentioned above. Following are two additional brief examples of the use of satellite-related information.

*Figure 8* illustrates trajectories derived from drifting buoys deployed during the Global Weather Experiment, 1979, and tracked by the Argos DCLS. As a by-product of these results, it proved possible to trace the origins of lobster larvae that developed into very significant fishery resources on some sea mounts in the eastern Atlantic. *Figure 9* illustrates generalized current systems derived from theoretical studies and supported by analysis of drifting buoy tracks. The fishery resources of this area are important, and understanding the ocean dynamics that support the fishery resources is an example of the useful application of satellite-supported observations.

Turning to quite another kind of biological application, the migration of whales from the Caribbean to the Gulf of Maine has been studied for a number of years. There are, however, very little environmental data on the scale required to piece together a meaningful picture of the relationship between the migration route and the environment. Such a data base is now becoming available with Coastal Zone Color Scanner (CZCS) (visible and thermal infrared) and AVHRR data. Unfortunately, the Nimbus 7 CZCS will certainly not last much longer; hence, these data will only cover a limited two- to three-year span with many gaps. A follow-on color scanner effort would contribute to an extension of the visible data (with collocated thermal infrared data). The idea of the ongoing research is to seek a correlation between the whale migration routes over a number of years and ocean temperature and color.

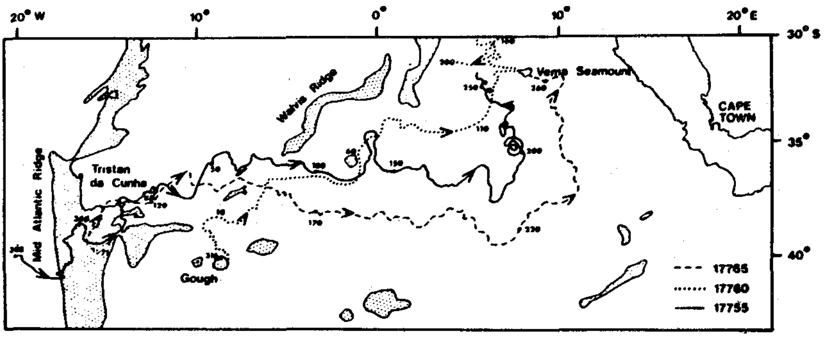



*Figure 8.* Drift tracks of three South African weather buoys deployed in the southeast Atlantic Ocean during the Global Weather Experiment, 1979. Bottom topography features shallower than 3,000 m are shown.

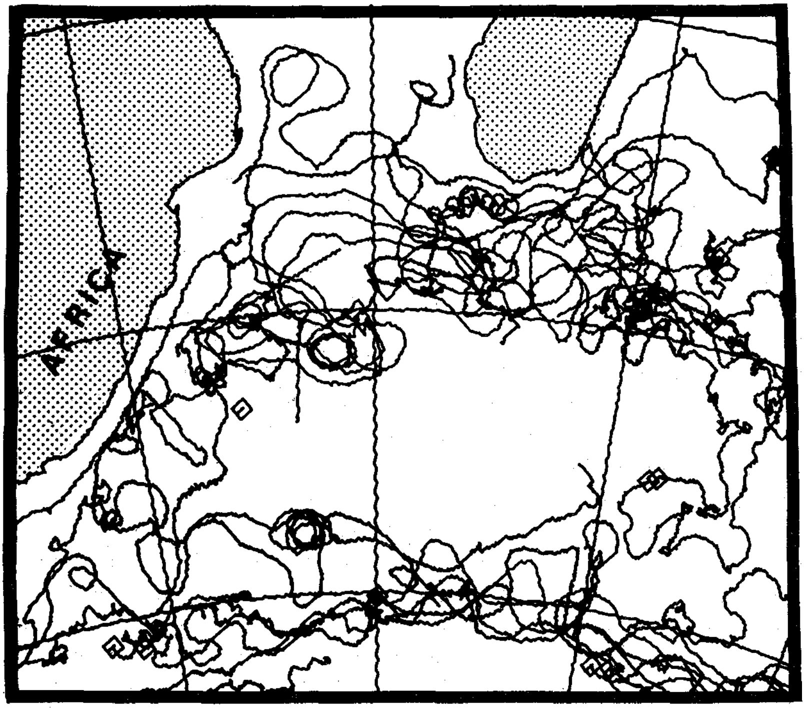



*Figure 9a.* Composite of drifting buoy tracks in the region off southwest Africa during the Global Weather Experiment, 1979. The observations during the GWE provided for the first time essentially synoptic views of ocean circulations over extensive regions; such information is essential for describing oceanic circulation and verifying models.

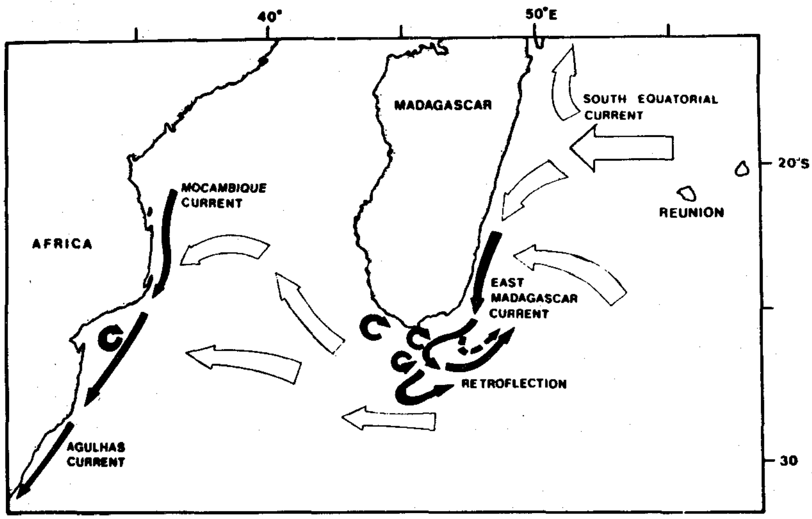



*Figure 9b.* Conceptual depiction of characteristic large-scale flow regimes off southeast Africa. Dark arrows depict narrow, intense currents; open arrows depict flow believed to show little directional variability. The conjectured western boundary current nature of the East Madagascar Current shows similarity to features of the Agulhas Current, which is related to important fishery activity.

# 3 VALIDATION/CONTROL OBSERVATIONS; ANCILLARY EXPERIMENTS

Satellite observing techniques often relate to different physical quantities, on different space and time scales, than do direct measurements *in situ*.

- ***A well-defined calibration effort is needed to support the satellite observing effort.***
- ***Care has to be taken to account for the specific physical characteristics of both the satellite and the direct observations in designing such comparisons.***
- ***Continuing direct observations are needed to provide a controllable, directly verifiable data base to serve as a monitor of the stability of the satellite data base.***
- ***For some types of observations, some*** special ***research efforts will be required to calibrate the applicability and accuracy of the algorithms used to extract useful physical information from the satellite measurements.***

A few comments below illustrate the examples that were discussed by the NOSS Science Working Group.

### 3.1 Wind Stress

The scatterometer radar observes the scatter cross section from the waves induced on the ocean surface by surface wind stress acting on the water. Larger waves, swell, and other surface features such as biological slicks may also influence the waves being observed and thus the radar return signal, as discussed above. Such other influences may be a function of wind speed, or, put in another way, the effects may be manifested differently as a function of wind speed.

***It was suggested in the discussions that the previous direct satellite comparisons in situ need to be continued and extended; that special attention has to be paid to the influences of short chop, swell, and surface biological activity; and that perhaps some wave tank experiments are in order.***

The analysis of comparisons during the Seasat operational period is also useful to set the context for planning a comparison program for future scatterometer efforts, as follows.

Previous experiments, Gulf of Alaska Experiment (GOASEX) and the Joint Air/Sea Interaction (JASIN) Experiment, have shown the Seasat A scatterometer backscatter to be related to wind speed and hence to surface stress. A successful future experiment would extend the wind speed range and provide stress estimates of a spatially averaged nature. Backscatter should be more highly correlated with such estimates than with wind speed. A speculative experimental scenario follows. On a large scale, bulk aerodynamic calculations from buoy data could give the friction velocity, $u_*$, with an uncertainty of 10-15%, averaged over about an hour, by supplying a directly obtained drag coefficient from dissipation measurements from a minimum of ships. With regular visits to each buoy, the necessary servicing, calibrations, and intercomparisons could be carried out. Routine meteorological observations and other synoptic data would also be provided by the ships. Eddy correlation measurements, taken whenever (aircraft) and wherever (stable platforms) possible, would enhance the spatial coverage and greatly increase the confidence in the "spatially equivalent" stress estimates.

A direct comparison between spatial satellite and surface time averages is not possible, and the latter must be made as equivalent as possible to a spatial average. A considerable planning effort would be required to ensure adequate spatial coverage, coincident with enough satellite passes, throughout the 4-25 m wind speed range. Particular attention must be paid to the higher speeds where much of the momentum transfer occurs. The stress acts in the direction of the mean surface wind and its magnitude is given by $\tau = \rho u_*^2$, where $\rho$ is the mean air density. At present the "best" techniques have uncertainties of at least ± 10% in $u_*$ (20% in $\tau$) and 10° in direction, but experienced personnel and considerable effort are required to achieve this accuracy. To illustrate, average surface winds need to be measured to better than ± 4%, requiring extensive direct calibration and maintenance and intercomparison of the sensors, which must be placed at platform locations where flow distortion is minimal. The influence of sea state and platform motion must also be determined. Similar considerations also apply to measurements of the mean wind direction. Without such precautions, errors of 100% in stress estimates are common.

Proven methods of estimating $u_*$ over the open ocean are the bulk aerodynamic (ships and buoys), the eddy correlation (aircraft), and the dissipation (ships). Each method has its advantages. The bulk method is the most straightforward, requiring the sea-air temperature difference (for a bulk estimate of the atmospheric stability) and the mean wind vector. An accuracy of 10% in $u_*$ is possible under steady wind conditions from hourly (and perhaps shorter) averages but, since it is a parameterization, departure from ideal conditions produces a great deal of "noise" in the stress estimates. For example, rapid variations in the mean wind vector can produce additional $u_*$ errors of 15% and 50% in daily and hourly averages, respectively. An averaging period as long as a few days may be required to reduce these effects.The dissipation method relates $u_*$ to spectral values of the wind velocity at frequencies in the $-5/3$ range, which are above those contaminated by platform motion. The inherent uncertainty is about 10% in $u_*$, but this technique appears to be able to follow closely the real stress averaged over 20 to 60 minutes. The data processing is somewhat involved and more responsive anemometers are required. The actual time of a satellite pass may not be representative of the period between passes and this can be determined from continuous time histories of the stress, which the dissipation method (and at lower frequencies, the bulk estimates) can provide. Time histories would also allow time averages to straddle a satellite pass, which may be more equivalent to the satellite's spatial average than a simultaneous record. Eddy correlation measurements from aircraft are highly specialized, but they can provide an almost instantaneous average over much of the area observed from a satellite. This is the most direct method and it can also be employed from available stable platforms, such as offshore oil rigs. The three methods have inherently different sampling characteristics and a combination would be desirable.

It is also possible that wind speed and direction cannot be obtained from radar measurements without some knowledge of the wave field. For example, the confused seas resulting from the tightly wound wind-stress pattern associated with the Queen Elizabeth II storm may explain the scatter in the winds observed there from Seasat. Recent simulation studies indicate that a determination of direction requires knowledge of the wave field (Hasselmann, private communication).

It may therefore be desirable to couple a spectral ocean wave model to the scatterometer algorithm in order to incorporate direction wave spectra information. Research along these lines, in a simulation mode, should be initiated as soon as possible.

## 3.2 Sea-Surface Temperature

The infrared or microwave radiance from the sea surface is a good measure of the effective radiating temperature, provided that other unrelated signals in the same passband are not received at the satellite at the same time. Ancillary observations are needed to correct for water vapor and other emitters in the atmosphere, for scattering by aerosol/haze particles, and for identifying very thin water or ice clouds that can interfere with infrared. There are few unwanted emissions (except commercial radio) that interfere with microwave, but the surface emissivity may be variable, the presence of large amounts of atmospheric liquid water in the field of view will interfere through absorption, and the spatial resolution is much larger than desired, even for a high-resolution instrument such as the LAMMR proposed for NOSS.

Moreover, the equivalent radiating temperature is usually the skin temperature, unless the upper several millimeters are well mixed. Verification measurements are generally not limited to skin temperatures. The effect of heavy seas from high surface wind on infrared emissivity is also not well known.

A well-distributed network of control stations, e.g., drifting buoys, moored buoys, and well-designed automatically communicating ship installations would provide very useful quality control for the satellite observations.

## 3.3 Color Scanner

Work remains to be done to clarify the relation between the return signals received by the color scanner and the various biological and physical processes taking place in the upper ocean layer. The NASA plan to implement direct experiments to study these processes, e.g., using lidar or Raman spectrometry, will be very important in the study of the vertical distribution of material, extending the depth range of observations and should eventually provide important direct observations for assistance in the interpretation of the color scanner observations.

In addition, efforts should be planned for ship or aircraft observations to support the interpretation of the larger-scale oceanic features seen on some of the images from the mid-ocean regions or near the major current systems.

## 3.4 Ancillary Observational Programs

Oceanic remote sensing satellites in the next decade offer the opportunity for unique supplementation to ship, buoy, and acoustic tomography experiments. In particular, if data collection and platform location systems are included on the oceanographic satellites, there will be strong incentives for marine scientists to use such systems for extensive direct experiments not only as control and validation of the satellite observations, but as major experiments in their own right. In section 2, some of the possible internationally coordinated experiments were mentioned. There could also be similar national experiments.

# 4
# AN OCEAN-DATA INFORMATION UTILIZATION SYSTEM (ODUS)

The plans for NOSS data processing and information extraction were very complete, but geared to operational use. Operational requirements are stringent—deadlines must be met for data input or the data are not used; late data, however, are usually salvaged and archived. The operational schedule and the resources available, in general, do not permit the most complete editing and verification of the satellite data streams, many of which are at a very high rate. Experience with meteorological operational data streams and with various research satellites shows that it is essentially axiomatic that any problems with the data stream, particularly problems associated with unwanted signal and with representativeness and sampling inadequacies, do not show up until the data are used for scientific studies. Often, it is then very difficult to go back to lower levels of processed data or to deconvolute the various processing steps, to find and fix the problems, or at least to identify and then discard suspicious data points. Therefore, since it was the interest of the NOSS Science Working Group to study the research possibilities of the NOSS instrument system and the NOSS operational data stream, considerable attention was devoted to data management.

Experience has shown that the routine engineering conversions (antenna corrections, electrical calibrations, navigation, timing, etc.) are essentially 100% reliable; even so, some checking is needed, for there have been occasional errors at this lowest processing level. More significant problems sometimes occur at the next processing level at which calibrations are applied to convert engineering signals into geophysical variables. Again, there are documentable cases in which problems have been uncovered, often *a posteriori*, when the data have been applied to scientific research and the scientist, having become aware of a problem, has tracked it down to a failure of a basic calibration system or to an undocumented change by a technician of one of the arbitrary parameters of a calibration system. These kinds of problems are not easy to find in the operational system. They are sometimes not that easy to find in delayed-time research processing either, but at least there is a better possibility since there is more time available. What is required, however, is that the earlier processing levels be archived and accessible, and all steps well documented.

Further complications arise in translating the measurements from many remote sensing systems to geophysical information. These come about because the measurement made is related to the desired variable through an often complex set of relationships. Derivations of surface wind or stress from radar backscatter are two examples, discussed in some detail in Section 2.2.1 and 3.1 above. The derivation of sea-surface temperature also has some of these complications. Extensive conversion algorithms are needed to process the actual satellite measurements and obtain the desired geophysical quantities. The NOSS implementation plan called for the completion of the information extraction algorithms at a rather early time, well before the Seasat and Nimbus 7 experience could be used in full to develop optimal algorithms. Thus, it was foreseen that the NOSS operational algorithms might not be optimal for research purposes, and that a separate development and verification of research algorithms would be necessary. These would have to be developed by the instrument science team, but verification and merging with related direct observations might need special computation or data handling support.

For these kinds of reasons, sketched here only very superficially, the NOSS Science Working Group agreed that a separate research Ocean Data Utilization System (ODUS) should be considered a vital addition to the NOSS science effort (note: the name ODUS has been used extensively in the discussions and is used here for convenience; if any special ocean data system is ever implemented, it might well be known by a different name). As discussions developed, it was seen that an ODUS could supply critical support to additional activity that would greatly enhance the NOSS information, e.g., by establishing a detailed, user-interactive catalog, by supporting efforts to compile and clean up relevant historical data. Finally, much discussion took place on how an ODUS could be organized, operated, and managed. It was agreed that it should be output-oriented (i.e., user oriented), rather than input-oriented (an operational mode more common to the national data archives). Agency participation would be essential (e.g., NASA Goddard Space Flight Center, Jet Propulsion Laboratory, and NOAA) but nonfederal groups should also be involved. For example, ODUS could be organized as a distributed system, with branch points at ocean research groups in universities.

Inasmuch as NOSS planning has been terminated, the question of a major data system facility has become dormant. The various properties suggested for an ODUS and the services it could perform are useful concepts, however, in developing a strategy for an ocean science satellite effort that might evolve in lieu of the proposed NOSS. The salient points of the various ODUS discussions, then, are summarized below.

*As a preface, it is fair to report that the NOSS Science Working Group felt strongly that adequate consideration of data handling, archiving in a user-oriented facility, and assistance in some aspects of large-scale data utilization would be vital in an oceanic science satellite system.*

The management and organizational desiderata of such a facility are unimportant to belabor at this juncture, but it may be noted that the NOSS ODUS, and any analogous sytem established for research satellites, were always conceived as an *addition* to any operational system, being fed from the processing level that produces gridded and timed geophysical quantities. The ODUS was conceived as a closure of the loop beween the satellite instrument and the ultimate research data user. Some of the tasks and desired properties of an ocean sciences research data system are set out below.

- *Compile important historical data sets, such as sea-surface temperature and wind, and analyze them to the extent needed to characterize the errors; identify and remove, if possible, systematic biases, and produce a historical time series to serve as reference base for future satellite time series. This task will be more labor-intensive (but with well-qualified people) than computer-intensive, but should be done in the context of a start-up phase of ODUS.*

- *Search out and collect important oceanographic and related data sets. For example, there were special operations of the NOAA meteorological satellites when the full-resolution AVHRR data were transmitted. These periods are documented, or in principle identifiable, but the data are not routinely available. What is not known for all cases is where the high-resolution data now reside, in what format they are, and how* *to get them. These potentially valuable data should be collected, cataloged, and archived for use by the community. There are many other examples of special data collections that should be searched out and accessed, or at least cataloged.*

- *Prepare a catalog of relevant data sets, with information as complete as possible describing the data and their format and explaining how they may be accessed. It would be desirable if a catalog could be constructed that would allow a user to query it, via an intelligent terminal (a minicomputer, for example), and receive some sample data sets for experimentation. In other words, a consumer-oriented interactive catalog, data sampling, and data supply system is envisioned. A start on such a system has been made at the Jet Propulsion Laboratory as part of the activity there in connection with Seasat data.*
- *Serve as a working data center or, as it were, an archive of* preferred *resort. The national data centers tend to become* repositories *of data rather than useful* working *archives. This is because the data streams are very large; the data flow into the data centers as they have been collected or reformatted for use in operations; that is, the national centers are input-oriented. It turns out, more often than not, that a researcher needing a subset of data finds the data distributed throughout such a large number of tapes, many thousands in some instances, that the data are in practice inaccessible. If the data were to be selected and organized in an optimal form for research use, the number of tapes would be drastically reduced. Then, the data set would become, in principle, accessible and easily used. Present estimates, based on experience at NCAR, are that many important data sets can be condensed by factors of two to 10 and some large sets can be reduced by factors of 100 or more by sampling such that most of the relevant information is retained.*
- *It is generally true that research data sets compiled for one research worker are also usable by many other workers. In fact, after some period of time for building experience, some 90% of data calls can be met by selected sets already in the working archive; this has been the experience at NCAR. The load on the archivist is thus reduced and the volume of tapes is reduced to manageable proportions. An ODUS working archive could meet most of the needs of the community, and still be of a manageable size. It could often serve as the* first *resort for research workers, and also serve as the channel, as needed, to the larger repositories operated by NASA and NOAA.*
- *Serve as a communication link, or interface, between the user and*

*the national archives, at least for some kinds of data sets and for some uses. ODUS should not compete with nor could it replace the large and very valuable national data centers. Rather, it could serve to relieve some of the demands on these centers by serving many special needs. Many of the data sets and/or analyses produced by scientists working with an ODUS would be appropriate and useful to store in the national data centers. If well-documented and compact data sets were in the national centers, and in their catalogs, they would be readily accessible to the user community. The experience of funding and operating such national centers has been that they have such limited resources that they cannot produce these sets on their own; once they have been produced by others, however, the national centers have no problems incorporating them in their collections.*

- *Be an integral part of the research user community. Earlier in this section, detailed discussion of the operational desiderata of an ODUS was eschewed; it may be permitted to note in closing this section, however that it was the general consensus of the Working Group that an ODUS will have the largest probability of working best if it is not fully a part of a federal agency, no matter how worthy are the initial intentions. Experience shows that budgetary and management pressures would almost certainly interfere with its freedom and functions, sooner or later. There is a challenge here for an innovative management and operational design for an ODUS that is practical for federal agencies to support, yet operates within the research community, insofar as such a modus operandi is possible in these times. We should look further into the future, however, to set realistic goals for a workable data sytem to support ocean science remote sensing and satellite data relay. To do otherwise would surely reduce the return value of the large investments that will be required to operate satellite programs in conjunction with the extensive national and international ocean research programs being contemplated.*

# 5
# IMPLEMENTATION OF FUTURE OCEANIC SCIENCES SATELLITE RESEARCH PROGRAMS

The successful Seasat and Nimbus 7 proof-of-concept of remote sensing of some important physical and biological properties of the oceans led to further explorations of specific experiments on the one hand and to practical applications on the other—e.g., TOPEX and NOSS, respectively. TOPEX is not yet a programmed activity and the deferral of NOSS leaves us at this time with no funded flight plans for near-future satellites devoted to oceanic sciences research. Some meteorological operational satellites will continue to provide sea-surface temperatures, the patterns of which are quite useful, but the absolute values of which are still fraught with some technical and considerable data processing problems. The meteorological satellites also provide a quite useful platform location and data relay capability, and ocean buoy programs are being planned to use this capability. These capabilities, though, fall far short of the potential of satellites to support oceanic sciences research.

The NOSS Science Working Group was briefed on the many considerations that entered into decisions on the NOSS orbit. Discussion of the many factors entering into flight design showed that often serious compromises are necessary when several instruments are combined in one spacecraft. Conversely, it is very expensive to fly each type of instrument on its own optimal orbit. Moreover, tracking, communication, and data handling facilities could be overtaxed by too many concurrent flights. Thus, detailed trade-off studies will be needed to decide which instruments or experiments can be combined, or which experiments could be flown on other geophysical satellites.

*To provide a context for management and engineering planning of future efforts, the oceanic science research community could provide a long-range program plan in which scientific goals are set and stages defined (development as well as timing sequences) by which these goals might be met. Such an effort is evolving in the context of the World Climate Research Program. Here, oceanic programs will be essential to meet the goals of understanding the physical processes of the atmosphere-ocean-earth climate system. There are other aspects of oceanic research and practical applications that would also benefit by similar planning efforts, mutatis mutandis.*

The NOSS Science Working Group discussed proposed modifications to the basic NOSS operational instruments. These modifications were designed to increase the research capability of the instruments. While such modifications were reviewed specifically in the light of the NOSS mission and spacecraft design, some of the recommendations of the Working Group have broader implications and are summarized below.

Additional discussions centered on the various pros and cons of a DCLS system operated as a service on, for example, a meteorological satellite, versus one designed more explicitly for oceanographic research and operated on a satellite devoted to oceanic sciences. Some conclusions as to the desired properties of an oceanic data collection and platform location system are summarized below.

## 5.1 Instruments

This discussion does not touch on all possible instruments to support oceanic operations and research, but is limited to the four planned for NOSS and one other considered as a possible addition.

### 5.1.1 Radar Altimeter

The NOSS altimeter and orbit were not designed expressly for a TOPEX-type experiment. The sun-synchronous orbit was chosen for other considerations, and the spacecraft configuration, required because of other considerations, would have resulted in high drag; these two factors limited the NOSS possible contribution to a TOPEX.

Since NOSS was to have been in a high-inclination orbit and to have viewed much of the polar regions, it was recommended that adaptive tracking be included to improve the altimeter tracking in regions of continental ice slopes.

*Should an altimeter be flown on a future satellite at high inclination, adaptive tracking should be included in the design to provide maximum information on the polar ice sheets.*

The NOSS instrument configuration included two altimeter units to assure the planned lifetime of five years, but only one antenna was included.

*It was proposed, and supported by the Working Group, that a second antenna be included, or that at least multiplex timesharing of the single antenna be provided to assure that the two electronic units could be operated simultaneously on occasion. Such intercomparisons would have made more secure the long-time coherence of the ensuing data series.*

### 5.1.2 Radar Scatterometer

Seasat experience showed that the antenna array could be improved by adding a seventh antenna, oriented along the nadir subtrack. Studies showed that the addition of this direction would allow most of the directional ambiguities to be resolved analytically, and would also provide an additional important benefit of nadir wind observations. This not only would have had intrinsic merit, but also would have greatly improved the design of comparison data sets taken *in situ*. *The Working Group supported these proposed improvements.*

### 5.1.3 Color Scanner

The color scanner had been designed originally for coastal work, partly because of the biological importance of this zone, partly because the high data rate of the instrument precluded fulltime operation anyway, and partly because it was not sure that color scanner observations in the relatively infertile open ocean would be of significant value. Recent experience has shown that the scanner images may be very valuable in midoceanic regions.

Much of the biological activity depicted by the visible channels of the color scanner is closely related to water temperature. Experience in analyzing the Nimbus 7 scanner images shows that a reliable temperature image, coregistered and synchronous in time, would be a most valuable addition. It is not at all certain, at this time, which technique would be a more useful one to obtain such a temperature image, use of the split window 12 micrometer channel, or addition of a 4 micrometer channel. The latter seems to be a quite viable possibility, based on the experience with this channel on a GOES sounder (VAS) (provided that sunglint at this wavelength can be avoided or accounted for in the information extraction algorithm), and the newer AVHRR on NOAA satellites.

Only approximately 10% of the signal received by the color scanner in the visible channels is related to biological backscatter of solar irradiation. The other portion arises from other scattering, represents a noise, and must be eliminated from the image before analysis of the biological information is possible.

*However, the biologists' noise is the meteorologists' signal. The "correction," if imaged, would reveal patterns of water vapor and atmospheric aerosol that would be invaluable for other work. It may well turn out that the aerosol information thus obtained from a color scanner may be the best way to obtain this information for the World climate Research Program (this possiblity is under detailed study now by a number of groups under the aegis of the WCRP). Thus, it should be assured that such valuable information is made readily available to other user communities.*

Of potential great importance to oceanographic research is the fact that the color scanner images contain information on circulation patterns in most regions of the oceans; an example is given in Section 2.2.4 above. Other images have revealed apparently conservative structures in the mid-Pacific gyre that can be tracked to provide useful dynamical information.

*The frontispiece poses the question: Are there oceanic structures visible from satellites as important to oceanographic research as cloud patterns are to meteorology? The answer may lie in large part in the color scanner images, particularly if good simultaneous temperature images are also available, and if the images are as readily available to users as cloud images are. Sampling strategies should be evolved to tap this large data stream for physical oceanographic research.*

*In summary, it appears as if the color scanner is an instrument of considerable potential both to biological as well as to meteorological and oceanographic research. Considerable exploratory work is now possible using the Nimbus 7 observations, and this work should reveal in the next few years more details about these potential uses and about how future flight plans should capitalize on this unique instrument.*

### 5.1.4 Large Antenna Multichannel Microwave Radiometer (LAMMR)

This instrument was designed to provide relatively high-resolution (compared with other microwave instruments, that is) sea-surface temperatures in all weather. The Working Group was not convinced that this would be the most valuable use of the LAMMR.

*Discussions of heat budget, Sections 2.3.5 and 2.3.6 above, indicated that high-resolution microwave observations are needed for derivation of moisture content in the lower layers and for information on precipitation. Temperatures of the sea surface would be a useful addition and would*

***complement information obtained from infrared systems flown on the same satellite and from other instruments, for example, on present operational satellites. The microwave observations would also be valuable for ice studies: the ICEX Report contains much discussion of uses of such a microwave instrument. The most profitable use of a LAMMR-type instrument may be in direct ice studies, or as part of a satellite system designed for climatological studies (e.g., heat budget, global precipitation, etc.). The information thus obtained would then also be of use and interest for oceanic studies.***

### 5.1.5 Data Collection and Location System (DCLS)

A DCLS was not planned explicitly for NOSS; however, in view of the possibility of adding instrumentation to the basic NOSS configuration, DCLS was given the highest priority. The technical and operational issues involving such a priority assignment are complex and, in any case, need and merit a detailed systems study; they are summarized here only briefly.

As an introduction, it is well to point out that a cooperative French/U.S.A. DCLS (Argos) is in operation now, continuing from the Global Weather Experiment, 1979, on the NOAA polar-orbiting operational meteorological satellites; it is expected to continue until the mid-1980s, and discussions are under way concerning further continuation. Location of a platform is based on analysis of the Doppler shift of a series of short-pulse signals containing the platforms' code name and data stream. The system was designed primarily to track constant-level balloons planned for extensive use during the Global Weather Experiment; since these balloons move with the wind, the system was designed for appropriate accuracy relating to expected wind speeds. This system accuracy, then, is much higher than needed for much slower platforms such as drifting buoys. The Doppler analysis method also precludes position analysis along and adjacent to the nadir subtrack (a swath about 1,000 km is excluded). Data relay, of course, is possible in principle at any position, although the software on the operational satellites or the ground processing system may reject signals that do not meet the geometrical restrictions imposed to obtain the accuracy required for balloon tracking.

***Mainly in view of the above considerations, it has been felt that a DCLS designed primarily for buoy tracking and data relay could result in considerable advantages. A buoy-oriented DCLS should, for example, have the following desirable properties:***

- Ability to accept several hundred platforms in view simultaneously (Argos is at present limited to fifty),
- Ability to accept signals over a wider receiver passband than Argos, with the benefit that simpler, lower-cost platform electronics would be possible,

- Higher data rate capability over a longer time,

  [Argos provides a relatively high data rate, but this is achieved by wide bandwidth of the pulsed signal, which in turn requires higher power of the platform transmitter. A different kind of tracking system might allow a satisfactory location from one transmission longer than the pulse used by the Argos system. Thus, an adequate data stream at lower power could be transmitted.]

- Capability for along-track locations.

  [This would greatly facilitate the optimal merging of the satellite data stream and those from direct observing systems.]

An essential feature of a DCLS design for *oceanic* programs is that it should allow a simple and inexpensive platform transmitter and still meet positioning and data relay requirements. Earlier sections in this report on programs using a variety of buoys or drifters stress the need to use these devices in large numbers, particularly for exploration of the larger circulation scales. While platform electronic costs are but one part of the total drifter cost, including deployment, economy in all facets of the system cost will facilitate their wide use. Cost, however, must include the satellite system development and flight costs; that is, comparison of relative costs of a buoy program using Argos versus one using a new DCLS must be based on analyses of the two total systems. At this time, comparison of system costs of Argos versus a new DCLS is still moot.

***Perhaps the most important overall factors in deciding what DCLS should be used would be the ability to track platforms along the satellite sub-orbital track, the ability to relay more conveniently a larger bit-stream, and the ability to track and obtain data relay from a large number of platforms in the field of view.***

Finally, a general comment. It would seem sensible that DCLS evolution should aim at one system, serving both operational needs (on NOAA operational meteorological satellites) and research needs, (e.g., the same DCLS included on oceanic research satellites to facilitate greatly the combination of satellite and direct techniques). It is possible that an evolution of the existing Argos system could meet the needs expressed above satisfactorily, and thus serve both operational and research needs. Or, it may well be that a different development is needed. It does seem that the operational role of a fleet of constant-level balloons as a meteorological observing system is doubtful, at least at the moment, while the role of ocean platforms is increasing rapidly. ***Thus, a future DCLS, be it Argos or otherwise, should be designed to accommodate the most probable future large-scale use—surface and pop-up drifting buoys.***

### 5.2 Support of Oceanic Experiments

In Section 2 of this report, a number of experiments are mentioned that would benefit greatly by concurrent satellite programs, e.g., the Tropical Experiment, the General Ocean Circulation Experiment, and Cage. In addition, TOPEX and WOED are satellite experiments. It is beyond the scope of this report to outline any time schedule or plan for such efforts. The NOSS Science Working Group did not include such matters in its charge and little discussion related to such matters took place. As mentioned earlier in this section, the research community could take the initiative in such matters.

*However, it was recognized that TOPEX seemed to be ripe for immediate technical and management planning, and would provide invaluable data sets applicable to a variety of problems. TOPEX observations would support the several experiments mentioned above.*

*Further, it also appeared to the Working Group that the scatterometer is an instrument of great promise for supporting several kinds of investigations, as well as for providing important operational data. It may be possible, for example, to include a scatterometer on a future NOAA operational satellite. Such a combination could be most useful, since AVHRR high-resolution temperature patterns would be available from the same satellite, and the Argos system would facilitate the direct observations needed in conjunction with the satellite measurements, as discussed in some detail in Section 3.1 above (provided that along-track data relay would be possible).*

*The possibility of adding a color scanner to one of the NOAA sun-synchronous operational satellites, on which the multichannel AVHRR SST system is used, also merits further study.*

SAR and LAMMR flights would be much more complex and would probably require special dedicated efforts.

### 5.3 Data Services

The several large-scale experiments discussed earlier and individual satellite efforts such as TOPEX will be greatly facilitated by a data and information system such as the one discussed in the previous section.

*The immediate future is not too soon to make a long-term commitment to initiate such a system. By doing so, much of the cleanup of historical data can be accomplished, and we can be ready for the addition of new satellite data sets. The experimenters designing and implementing the many new programs will have had the opportunity to influence the data facility as to their future needs in connection with the specific experiments to be conducted. Even more critically, time will be available to train new data experts and have an experienced team ready for the large-scale experiments and data streams probable in the next decade. This is not a minor matter,*

***cally interested, but data-user-oriented experts are rare.***

The expertise in the meteorological community is one possible starting point. Close cooperation between the meteorological and oceanic research and data communities in the future will be beneficial to both.

The experimental needs and data requirements of the major oceanic experiments proposed as part of the World Climate Research Program provide one timely impetus to get started on building a realistic but adequate oceanic sciences datafacility. Further programmatic stimulations are the possibilities of implementing TOPEX and scatterometer flights, and the need to capitalize on the forthcoming improvements in the operational sea-surface-temperature systems being implemented on the NOAA spacecraft. ***A research-oriented data facility operating in connection with the operational systems, insofar as possible, will extract the maximum amount of reliable scientific information from such efforts.***

# 6
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## 6.1 Scientific Contributions

Significant scientific contributions were received from the colleagues listed below, who are listed in the approximate order in which their material was used in the report. Contributions were in the form of written material or extensive conversations about some of the matters covered in the report.

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## 6.2 Sources of Illustrations

| | |
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| Cover | Laura Lee McCauley, *NCAR* |
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# 7
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