THE PROMISE OF SATELLITE OCEANOGRAPHY

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Abstract: The goal of the Oceanic Processes Program at NASA is to evaluate the utility of spaceborne techniques for observing the oceans, and to apply these techniques toward advancing our understanding of fundamental oceanic behavior. This paper describes some of the oceanographical problems amenable to solution using satellite observations, such as the use of satellite altimetry to determine the surface geostrophic current and scatterometry to determine the surface wind stress. This data, together with complementary data obtained in-situ and relayed through satellite location and data collection systems, will enable us to determine the global circulation of the ocean. In addition, the use of color scanners to determine primary productivity and physical-biological interaction in the ocean is discussed.

Introduction

Oceanic 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 of broad scale surface features such as wind stress, sea level, surface waves and currents, and temperature at time intervals which are short enough to be effectively continuous gives an enormous potential advantage over shipborne techniques. High resolution images of temperature or color or microwave emissivity allow unique visualization of near-surface processes such as internal waves and 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, which are rapidly becoming intolerably expensive. Communications with sensors on fixed and drifting buoys, and the location of non-fixed 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 essentially 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 intercomparisons and confidence building case studies. These will require long-range commitment by leading oceanographic scientists and satellite instrument specialists.

Recent experience with sensors on GEOS-3, Nimbus-7, and Seasat designed for ocean observation 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 standards 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 (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.

Research Activities

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 underway 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.

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. 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 waves 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 distorted 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 waves 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 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, $a_k$, 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.

**Mesoscale Variability**

The most energetic mesoscale oceanic eddies are found in the vicinity of strong currents and probably have their source in instabilities. Over most of the ocean, the level of eddy energy is lower; recent studies 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 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 conclusion 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 50 km and a time resolution of approximately three days.

Observations of Sea Level (Radar 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 field 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).

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 the scientific goals of TOPEX.

A 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 altimetry 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.

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.

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 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.

Data Collection and Location Systems

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. 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-1980's. 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 many hundreds of 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.

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.

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, 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 thermistor chains to obtain temperature profiles, subsurface flotation with tracking and data relay via the sound channel.

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

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 could 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.

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 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 (WOCE) 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 designed 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.

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.