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REMOTE SENSING FOR OCEANOGRAPHY: AN OVERVIEW

The problem of obtaining proper sampling of the averaged quantities treated in our analytical and numerical models is now the most significant limitation on advances in physical oceanography. Within the past decade, many electromagnetic techniques for studying the earth and planets have been applied to the study of the ocean. Satellites now promise nearly total coverage of the world's oceans in only a few days to a few weeks of observations. This article reviews the early and current techniques applied to satellite oceanography and describes some future systems that will be orbited during the remainder of this century. Both scientific and technologic capabilities are discussed.

INTRODUCTION

Oceanic processes have traditionally been investigated by sampling from instruments in situ, yielding quantitative measurements that are discontinuous in both space and time. The past two decades have seen the development of new observing systems such as the aircraft expendable bathythermograph, current meters, and subsurface floats that give continuous records in one dimension, either instantaneously in the vertical, or at a fixed point, or that approximately move with a water parcel. Arrays of these instruments have greatly increased our awareness of the space-time variability in the oceans, whether it is due to internal waves, mesoscale eddies, or fluctuations in the general circulation itself. The problem of obtaining proper sampling of the averaged quantities treated in our analytical and numerical models is now 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 features (e.g., wind stress, sea level, surface waves and currents, and temperature at time intervals that are short enough to be effectively continuous) gives an enormous potential advantage over shipborne techniques. High-resolution images of temperature, color, or microwave emissivity permit a 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 a new kind of strategic planning for ship operations. Communications with sensors on fixed and drifting buoys and the location of nonfixed systems by means of satellites make possible all sorts of composite subsurface measurement systems that would otherwise be quite impractical.

Remote sensors operating from space will never replace direct measurements and acoustic remote sensing because the ocean is essentially opaque to electromagnetic radiation. However, spaceborne remote sensing systems and data relay and platform location techniques should play substantial roles that need to be 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, and 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.

Recent experience with sensors on Skylab, GEOS-3, Nimbus-7, and Seasat designed for ocean observation underlines the need to include from the beginning explicit planning for validation/control observations and a substantial data collection, archiving, and distribution 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, the necessary corrections have been applied, and the 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 it is attractive as a unique complement to information derived from direct observations. The process of assimilation and adjustment to these new opportunities will be a long and sometimes painful one.

The following descriptions of possible research activities are not ordered according to priority but illustrate a range of important and challenging scientific applications. Several 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 because they have been studied by various scientific working groups supported by the National Aeronautics and Space Administration (NASA) and other agencies.[1-6]

WIND STRESS

Wind stress at the surface is one of the major driving forces of oceanic circulation. There are no systematic observations of wind stress 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, but they are noisy (i.e., they may contain undetectable errors) and uncalibrated (e.g., for ship effects) and they must be processed carefully before use.

Remote sensing systems mounted on near-polar orbiting satellites can sample rapidly and frequently the entire earth's surface. Although numerous satellite-borne active and passive systems (altimeters, radiometers, scatterometers, and synthetic aperture radars) have measured wind speed, microwave scatterometers have demonstrated a decided advantage because of their ability to measure the vector winds (speed *and* direction) needed as inputs for oceanographic and meteorological studies. A novel technique for determining wind speed and direction using synthetic aperture radar is described by Gerling in Ref. 7 and in another article elsewhere in this issue.

The use of active microwave systems for the measurement of oceanic winds resulted from the World War II development of radar systems for air defense. Research into the cause of sea clutter was conducted by the United States and the United Kingdom after the war. Experimental studies in the 1950s and 1960s established an apparent correlation between backscatter at moderate incidence angles and surface wind speed. An extensive series of airborne radar measurements by the Naval Research Laboratory using a four-frequency pencil-beam scatterometer and by NASA's Johnson Space Center using an airborne fan-beam scatterometer at Ku-band frequencies established an approximate power-law dependence of normalized radar cross section on wind speed. In the early 1970s, NASA developed an improved pencil-beam aircraft scatterometer that was stable and that demonstrated good absolute calibration. Field experiments improved and refined the approximate power-law relationship between the normalized radar cross section and the wind speed at incidence angles from 20 to 70 degrees. In addition, by obtaining data from circle flights, the relationship between the normalized radar cross section and azimuth angle relative to the wind was examined. The amplitude of the normalized radar cross section varied with both wind speed and azimuth angle, and the nearly harmonic variation with azimuth angle made it possible to determine wind direction by radar measurements of the same spot in the ocean at two azimuth angles.

A pencil-beam radiometer/scatterometer was flown aboard Skylab missions SL-2, SL-3, and SL-4 during 1973-77. Because the scatterometer was a single beam, only a single measurement of the normalized radar cross section at one value of azimuth angle was obtained from each portion of the sea surface. Nonetheless, the experiments demonstrated that wind speed scatterometry from space was feasible.

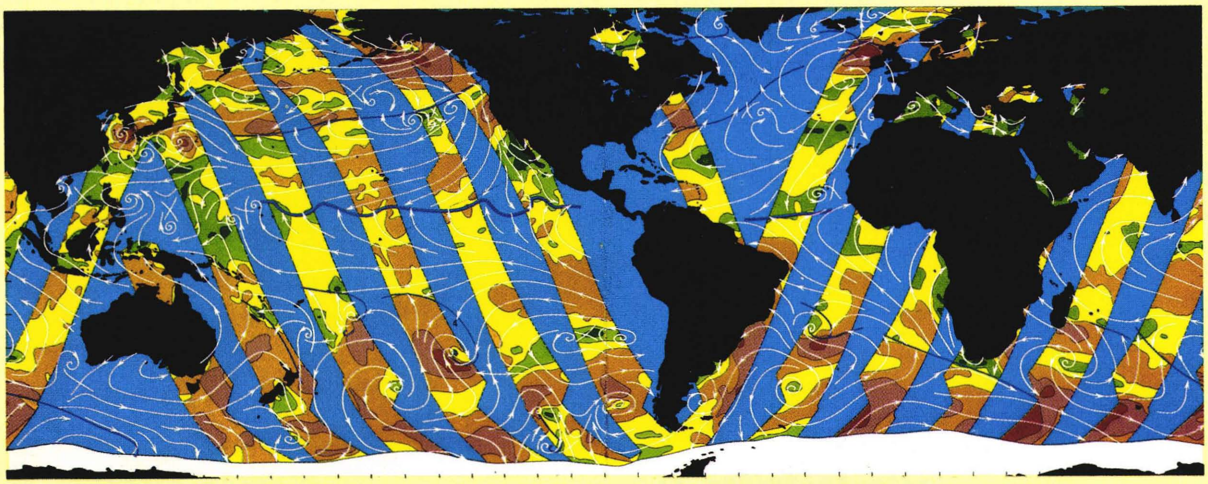
The Seasat-A Scatterometer System, a four-antenna, fan-beam, dual-polarized, Ku-band system, was flown aboard Seasat from June to October 1978. The normalized radar cross section measurements from the fore and aft beams were combined to give estimates of wind speed with up to four possible directions (unfortunately called "aliases")—a major accomplishment. Using Seasat-A Scatterometer System data, the first global, nearly synoptic maps of wind speed and direction have been constructed by P. Woiceshyn and others at the Jet Propulsion Laboratory (see the text insert).

In 1990, the U.S. Navy plans to fly NROSS, an oceanographic satellite that will carry NSCAT, a NASA scatterometer. An additional antenna on each side of the spacecraft (making six in all) will reduce the alias problem to an ambiguity of 180 degrees for about 95 percent of the measurements. The normalized radar cross section will be measured with a spatial resolution of 25 kilometers. In the opinion of scientists who are trying to develop better models of the ocean circulation, one of the greatest needs 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 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 ocean surface gravity-capillary waves into stress/speed), 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 on variations in the intensity and density of these structures as a function of wind speed. One type of structure in-

GLOBAL MARINE WINDS

In 1978, the Seasat-A Scatterometer System obtained the first global measurements of ocean wind data. Wind speeds were calculated from radar reflections from the small wind-driven waves that roughen the sea surface. The scatterometer estimated wind speed with an accuracy of ±2 meters per second and wind direction to within ±20 degrees. This image is the first comprehensive view of the winds over the world's oceans and was constructed from data collected by Seasat. Seven orbits over the world's oceans during a 12-hour period on September 14 and 15, 1978, were used. The lowest wind speeds are shown in green and yellow, the highest in pink and red. White streamlines that parallel the wind flow have been interpolated across areas not covered by the satellite path (depicted in blue).



volves 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 the 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 that 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 the distribution 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 centimeters) increases with wind stress, but the amplitude at breaking decreases with wind stress. The 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. On the other hand, short gravity waves have growth and decay times longer than this, so if they are accompanied by a dominant longer gravity wave (as is usual in the ocean) the 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, resulting in a substantially increased density of microscale breaking, parasitic capillary waves and in 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 effects. The modulations provide the basis of operation for the scatterometer radar. It is this melange of structures that provides the backscattered 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 show a great deal of variability. Enough is known about these structures to be confident that they are also influenced strongly by the slope of the dominant wave present or Huang's "significant slope" parameter.[8] The dependence is not taken into account in the analysis of scatterometer results.

The same modulation of the capillary-gravity wavelets by longer gravity waves and by swell is also partly responsible for the imaging of the dominant ocean wave field by synthetic aperture radar. Through Fourier transformation of the imaged wave field, it is possible to determine the direction of the accompanying wind field (see the article by Gerling in this issue for details).

It is evident that there is a considerable need for further research in this area to establish better the characteristics of the 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 eddies could be attributed to direct forcing by the variable winds, a conclusion that requires 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. Admittedly, this possibility was based on a few observations that 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 that extrapolated the observed spectral slope at scales on the order of 1000 kilometers down to scales on the order of 100 kilometers.

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, which would require a spatial resolution of approximately 50 kilometers 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 the Ocean Topography 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 (see the figure in the Sea Surface Topography text insert). Accurate knowledge of the satellite orbits and of the earth's gravity field is necessary to extract maximum information from satellite altimeter observations. These matters, as well as the scientific problems to be addressed by TOPEX, are discussed in detail in Ref. 1. The Seasat altimeter showed a precision of about 10 centimeters in measuring the distance between the instantaneous sea surface and the satellite. It is estimated that this precision has to be increased to about 2 centimeters to meet most of the scientific goals of TOPEX.[1]

The altimeter measurement of primary importance to the oceanographer is the departure of the sea surface elevation from the geoid: the dynamic topography field. The large-scale to mesoscale circulation of the ocean is nearly in a geostrophic balance; that is, to the lowest order, the horizontal pressure gradients are nearly balanced by the Coriolis acceleration, resulting in a horizontal sea surface height gradient perpendicular to an ocean current. Because of this balance, for example, the right edge of the Gulf Stream (looking in the direction of flow) is higher than the left edge by approximately 1 meter. Mesoscale eddies have smaller height signatures, on the order of tens of centimeters. The precision of the TOPEX altimeter will certainly allow the measurement of these fields and the subsequent determination of the surface geostrophic current field.

Another feature of the altimeter is its ability to provide 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 maritime operations and for the study of the development, propagation, and effects of ocean events such as major storm surges.

Radar altimetry could also provide useful information on the topography of the great continental ice sheets of Greenland and Antarctica that is difficult to obtain by conventional geodetic leveling.

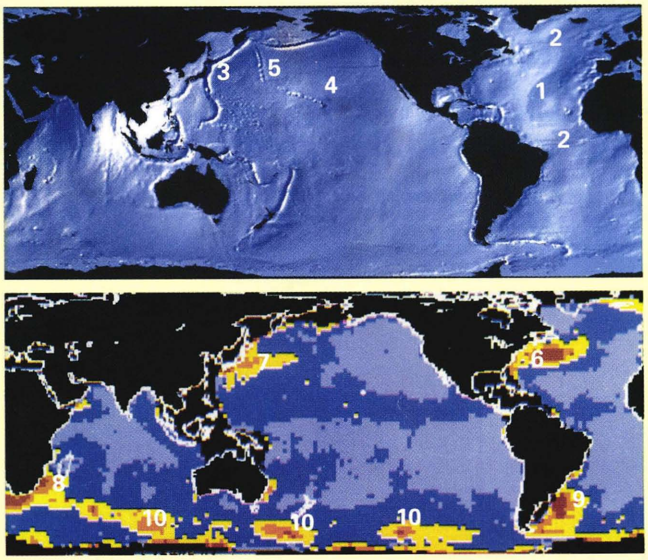
BIOLOGICAL OCEANOGRAPHY AND OCEAN COLOR

The Coastal Zone Color Scanner operating on Nimbus-7 is providing a most intriguing new data set. The scanner was planned primarily for biological investigations, 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). In addition, important information is made available on oceanic structures, sea surface temperatures, and gross aerosol distribution (see the figure in the Phytoplankton and Temperature Patterns text insert).

A global and selected regional assessment of living marine resources is a key problem in biological oceanography. Satellite ocean-color sensors can provide the necessary data. It is abundantly clear from years of experience with shipboard observations that ocean areas with the most biota of interest are also the areas

SEA SURFACE TOPOGRAPHY



Sea Surface Topography (top): The height of the sea surface relative to the center of the earth is not only a function of ocean currents but also of the earth's composition. Changes in composition have an effect on the earth's gravity field and are reflected in the relief of the sea surface. This map of the average sea surface topography—the marine geoid—was produced from 70 days of Seasat altimeter data. The results clearly show the relationship between the ocean surface and the changes in gravity caused by the underlying ocean-bottom topography. Since the ocean surface predominantly follows the earth's geoid, this dramatic image is especially useful for charting poorly surveyed areas of the world such as the Southern Ocean surrounding Antarctica. By mapping the ocean surface from space, scientists obtain valuable information about topography and composition of the ocean floor. For example, over a submarine trench, the geoid depresses the surface as much as 60 meters closer to the center of the earth. In contrast, seamounts can cause the surface to bulge as much as 5 meters above average sea level.

This image, which has a spatial resolution of about 50 kilometers, was computer generated, and the changes are revealed as if the map were illuminated from the northwest. Seen here are the characteristic features of the ocean floor: the mid-ocean ridges, trenches, fracture zones, and seamount chains. Clearly visible are the mid-Atlantic ridge (1) and associated fracture zones (2), the trenches along the west and northwest margins of the Pacific (3), the volcanic Hawaiian Island arc (4), and the Emperor seamount chain (5).

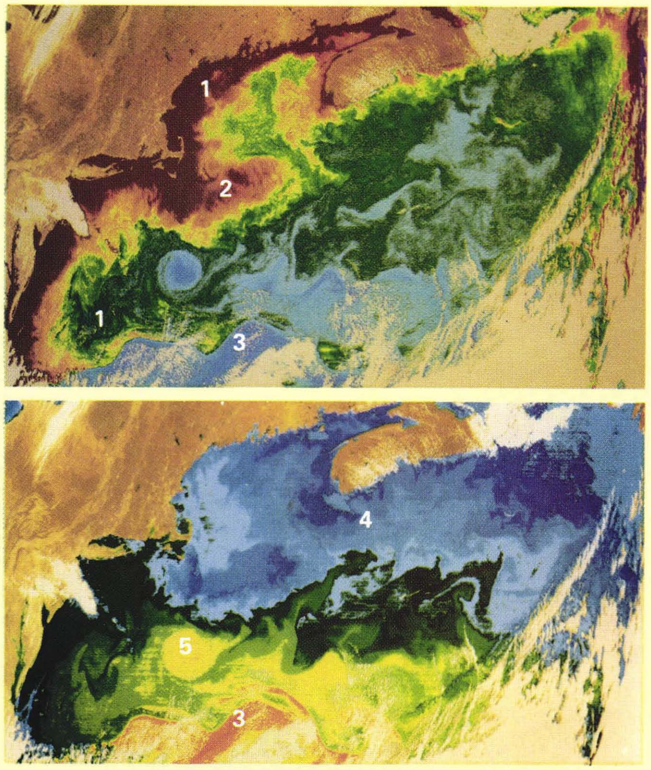
Ocean Currents (bottom): Superimposed on the mean surface, or the marine geoid, there is a time-varying sea surface topography that is directly related to the variability of ocean currents. These time-varying currents can be calculated from data collected during repeated orbits of the satellite. The mean or constant height along many repeated orbital paths is principally due to the (constant) geoid, while the ocean surface variations due to changing currents are the deviations above and below this mean. Shown here is a global map of the variability of the sea surface topography about the mean for one month during September and October 1978. The largest deviations (10 to 25 centimeters) are associated with the strong western boundary currents (yellow and orange). These currents include: the Gulf Stream (6), the Kuroshio Current (7), the Agulhas Current (8), and the Brazil-Falkland Confluence (9). Large variations also occur in the West Wind Drift Current around Antarctica (10). An important revelation from Seasat's mission is the relatively small variability (light blue) over most of the oceans during this one-month period of altimeter measurements.

that are dynamically the most complex and variable. Consequently, 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 variable 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); observations of these factors are hardly accessible to shipboard sensing and are inaccessible to remote sensing.) The variability influences both practical problems associated with sampling and estimating abundance within the environment and with theoretical considerations related to the structure and dynamics of phytoplankton ecology. Also, the variability of phytoplankton communities may be the key to understanding the relative importance of physical and biological factors in structuring the marine food web. There is also evidence that the successful modeling of phytoplankton dynamics and the predictive linkage of

PHYTOPLANKTON AND TEMPERATURE PATTERNS



These two images show the distributions of phytoplankton pigments (top) and sea surface temperatures (bottom) in the North Atlantic off the U.S. coast. They were made from data collected on June 14, 1979, using the Coastal Zone Color Scanner aboard NASA's Nimbus-7 satellite. The scanner measures light reflected from within the upper few meters of the ocean in four narrow color bands, as well as infrared measurements of sea surface temperature. This information is recorded for each 800 meter pixel (picture element) across the 1556 kilometer swath beneath the spacecraft. The resulting digital image is then computer-processed to generate quantitative pigment concentration values for each pixel, which are color coded according to concentration range.

(Top) In this image of pigment concentrations, regions of high concentrations (above 1 milligram per cubic meter) are shown in brown; intermediate levels in red, yellow, and green; and lowest levels (less than 0.01 milligram per cubic meter) in blue. Land areas are depicted in light brown and cloudy regions in white. Where phytoplankton are the major absorbers of light in the ocean, this estimate is within 30 percent of values measured from ships. In regions where sediments and other material affect ocean color, the estimates are accurate to within a factor of two or three.

The high concentrations are seen to lie along the Continental Shelf (1) and above Georges Bank (2) southeast of Cape Cod (2). This high, near-shore productivity results from increased nutrient availability due to river runoff and mixing of deeper, cooler nutrient-rich waters by tides and wind. In deeper waters, such as those between the Gulf Stream (3) and the Continental Shelf, nutrients required for plant growth are not mixed as rapidly into surface waters, and phytoplankton concentrations are much lower. The Gulf Stream and Sargasso Sea to the south are relatively nutrient poor, and the phytoplankton concentrations are at a minimum.

(Bottom) In this image of sea surface temperature, the warmest water (about 25°C) is color coded in reds, cooling through shades of yellow and green. The coldest waters (about 6°C) are in shades of blue. A highly variable region can be seen southeast of Georges Bank where the warm northward flow of the Gulf Stream swings to the east (3) and confronts cool water extending southward from the Labrador Current (4). Regions of strong tidal mixing and upwelling of deeper waters appear as cool areas, seen along the eastern edge of Georges Bank and south of Nova Scotia. These temperature patterns reflect physical processes (currents and mixing) that affect phytoplankton distributions and contribute to the maintenance of the very productive fishery on Georges Bank.

Conspicuous in both images is a circular Warm Core Ring (5) south of Cape Cod. These isolated eddies spin off from the north side of the Gulf Stream and introduce more saline, Gulf Stream/Sargasso Sea water into cooler, fresher Shelf-Slope waters. They are relatively common features in this region, and their productivity and ocean color often contrast markedly with the surrounding water. Rings range from 100 to 300 kilometers in diameter and can persist for years. They rotate clockwise once every two to four days with current velocities of 0.5 to 1.0 meter per second. Warm Core Rings usually move toward the southwest and eventually become reabsorbed into the Gulf Stream off Chesapeake Bay. Warm core rings influence the exchange between Shelf and Slope waters in the Atlantic and play a significant role in the area's biological productivity.

phytoplankton production to higher trophic levels have 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, and can include both vertical and horizontal measurements; however, they 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 along-track measurements, and can be relatively precise (although accuracies are the subject of ongoing research); however, they 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 and can provide repeated routine coverage of regional areas (including those areas that are far from our oceanographic research institutions); however, it is relatively less accurate without concurrent ship or aircraft data, is limited by cloud coverage, and requires 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 the illumination of the relationship between 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 would clearly be important contributions to biological oceanography.

DATA COLLECTION AND LOCATION SYSTEM

A data collection and location system on Argos was implemented on the National Oceanic and Atmospheric Administration's operational satellites for the Global Weather Experiment in 1979 in cooperation with French colleagues who supplied the hardware and undertook the data processing, a joint arrangement that 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; 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 science programs in direct and remote sensing. For example, the data collection and location system for ocean sciences must be able to view a larger number of platforms than Argos does, up to many hundreds simultaneously, or some regional projects being considered will not be able to use sufficient numbers of observing sites.[4] 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 very useful for extensive oceanographic observations if the design of the data collection and location system 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 the long ranges involved in mesoscale and basin-scale oceanography 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 current techniques, but only if 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 were demonstrated in the Global Weather Experiment. The buoy program for that experiment was invented and implemented for meteorological purposes. However, the data fields 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 the 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 desirable, thereby probably limiting the future use of very frequently located subsurface drifters to regional studies. However, for aiding in the description of the mean general circulation, including lateral eddy dispersion, the use of satellite-located 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, the National Oceanic and Atmospheric Administration, and the Office of Naval Research and that involves collaboration by a group of researchers as well as sensor and buoy engineers)[9] and assuming that a suitable data collection and location system is available, a substantial program to produce worldwide maps of statistics of ocean circulation for four frequency bands would be feasible. The four bands are (a) one cycle every 2 to 40 days, a spectral band containing the results of direct atmospheric forcing; (b) one cycle every 40 to 150 days, the temporal mesoscale band; (c) one cycle every 150 days to the length of a feasible program (for example, 3 to 5 years), the secular climatic variability scale; and (d) 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 to 200 meters. Drifters would be distributed at the surface, in the thermocline, and at an abyssal level, 3000 to 4000 meters for example. A satellite data collection and location system or an acoustic relay, or a combination, would be used.

FUTURE PLANS

Satellite-borne observation and communication systems offer a variety of techniques to observe and map qualitatively, with high resolution, many oceanic features of importance and to make measurements that are the basis of quantitative information. However, the techniques are limited essentially to surface manifestations; hence there will continue to be a strong need for direct measurements using ships, buoys, moorings, etc., as well as for subsurface remote sensing by acoustic methods.

There are several large-scale national and international experiments being planned in the context of the World Climate Research Program[10] for which satellite techniques offer a valuable and, in some cases, unique capability: a large-scale study of the heat budget in the North Atlantic, a tropical ocean-atmospheric experiment with emphasis on the Southern Oscillation, and a World Ocean Circulation Experiment for which TOPEX and the extensive use of satellite-tracked drifters would offer unique contributions.

For any large-scale ocean circulation study, it is imperative that we obtain both the global surface wind stress field and the global dynamic topography field. These fields are the necessary boundary conditions for any ocean general circulation models that may be developed in the near future. TOPEX, NROSS, and the European Space Agency's ERS-1 seem to be the most feasible satellite techniques for early implementation.

For the 1990s, NASA is conducting a study for a comprehensive Earth Observation System[6] (formerly called System Z) that will consist of

1. A set of instruments in low, sun-synchronous earth orbits dedicated to long-term remote sensing of various global phenomena of land, ocean, and atmosphere;
2. A global set of land, ocean, and atmosphere instruments in situ to complement the orbiting instruments;
3. An international community of scientists who conduct the research by analyzing the information gathered by techniques 1 and 2 above and by controlling their operation;
4. A data communication/computation network that collects the data from techniques 1 and 2 and any required data from other sources (such as operational earth-sensing satellites), operates on the data to increase their information content, stores the information in various databases and archives, and distributes the information to the scientists mentioned in item 3 above.

The intent of the system is to be interdisciplinary, because most geophysical processes involve exchanges occurring at the atmosphere/ocean or atmosphere/solid earth interfaces.

During the past decade, remote sensing of the oceans has been demonstrated to be feasible. It is now time to implement routine satellite observations during the remainder of this century. The process will be difficult but the rewards enormous.

REFERENCES

1 *Satellite Altimetric Measurements of the Ocean,* TOPEX Science Working Group, NASA, Jet Propulsion Laboratory, California Institute of Technology, Pasadena (1981).

2 *Scientific Opportunities Using Satellite Wind Stress Measurements over the Ocean,* NASA Satellite Surface Stress Working Group, Nova University/NYIT Press, Ft. Lauderdale (1982).

3 *The Marine Resources Experiment Program (MAREX),* NASA Ocean Color Working Group, NASA/Goddard Space Flight Center, Greenbelt, Md. (1983).

4 *Satellite Data Relay and Platform Locating in Oceanography,* NASA In Situ Ocean Science Working Group, Nova University/NYIT Press, Ft. Lauderdale (1983).

5 *Oceanography from Space. A Research Strategy for the Decade 1985-1995,* Satellite Planning Committee, Joint Oceanographic Institutions, Inc., Washington, D.C. (1984).

6 *Earth Observing System,* Science and Mission Requirements Working Group Report, NASA Tech. Memo 86129, NASA/Goddard Space Flight Center, Greenbelt, Md. (1984).

7 T. W. Gerling, "Structure of the Surface Wind Field from the Seasat SAR," *J. Geophys. Res.* (in press).

8 N. E. Huang, S. R. Long, C.-C. Tung, Y. Yuen, and L. F. Bliven, "A Unified Two-Parameter Wave Spectral Model for a General Sea State," *J. Fluid Mech.* **112**, 203-224 (1981).

9 J. C. McWilliams and J. E. Masterson, *Plan for the Development and Utilization of Ocean Surface Drifting Buoys (DRIFTERS)*, University Corp. for Atmospheric Research Publication, Boulder (1982).

10 *Large-Scale Oceanographic Experiments in the World Climate Research Programme (WCRP)*, JSC/CCCO Study Conf., Tokyo, May 10-21, 1983, WCRP Publications Series No. 1 (1983).

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