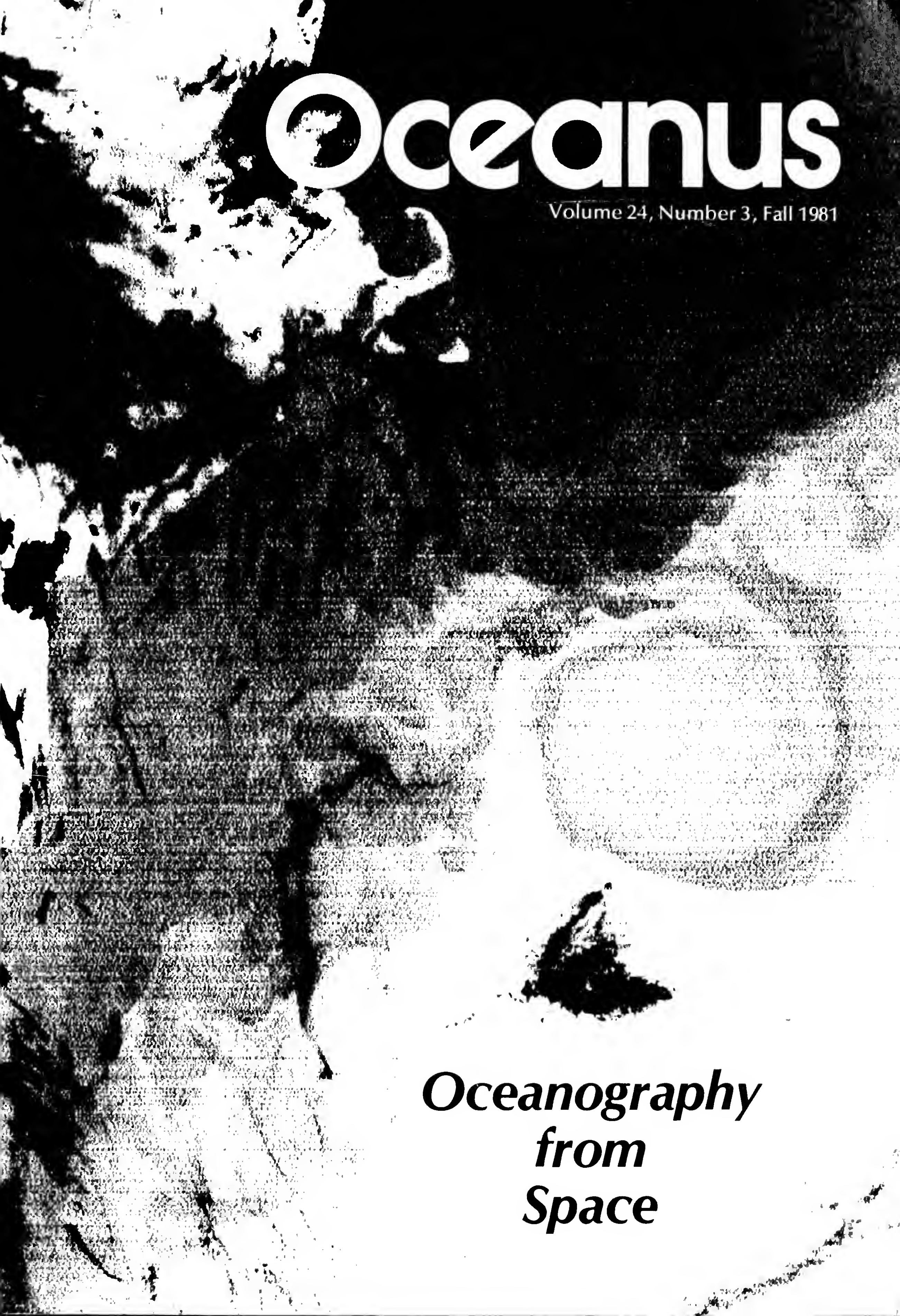
Oceanus

Volume 24, Number 3, Fall 1981



Oceanography from Space

Oceanus®

The International Magazine of Marine Science
Volume 24, Number 3, Fall 1981

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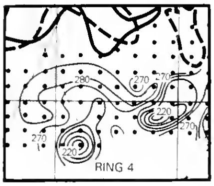

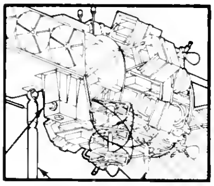

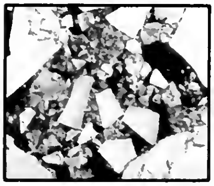

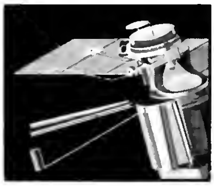

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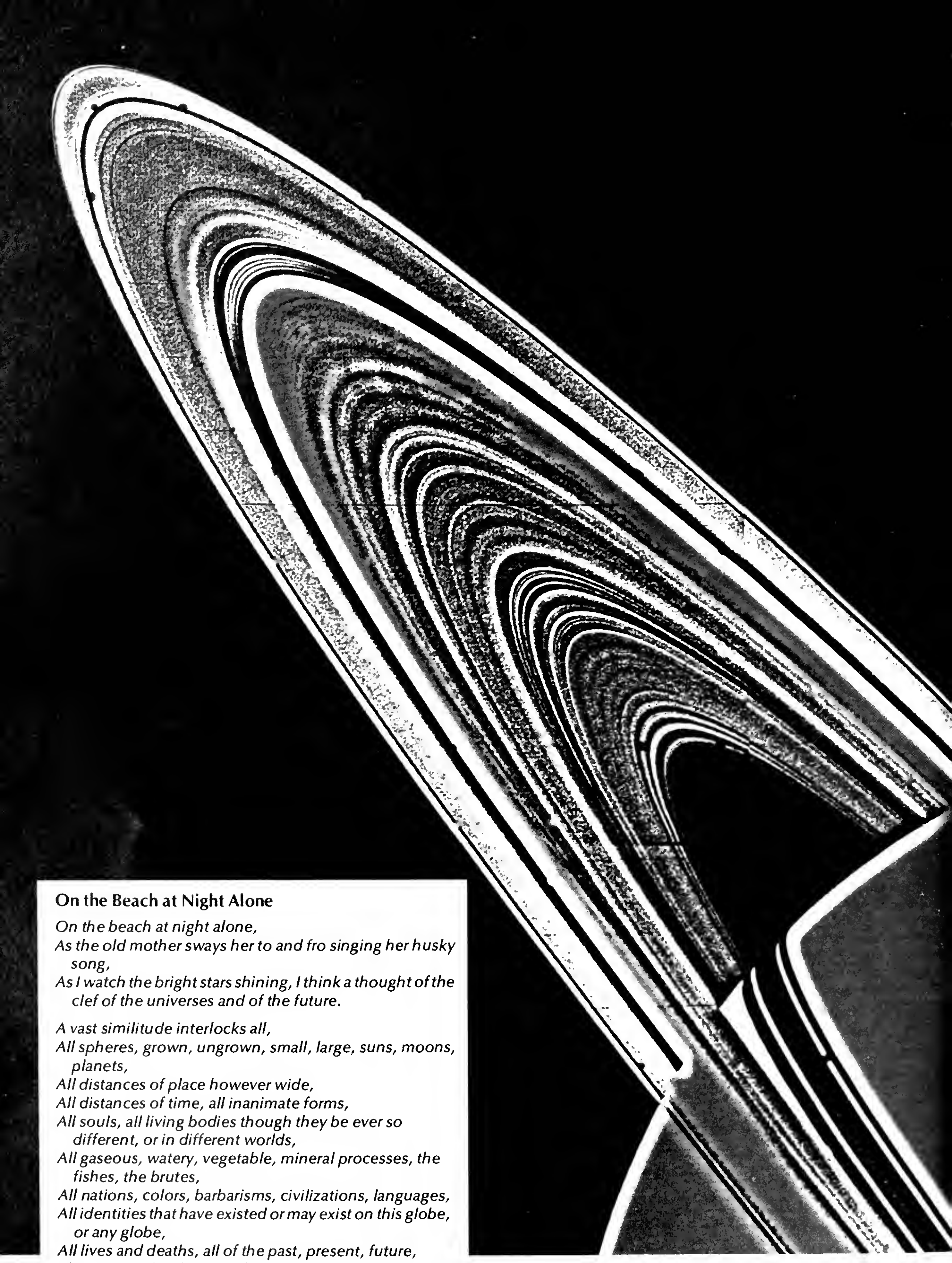

On the Beach at Night Alone

On the beach at night alone,
As the old mother sways her to and fro singing her husky song,
As I watch the bright stars shining, I think a thought of the clef of the universes and of the future.

A vast similitude interlocks all,
All spheres, grown, ungrown, small, large, suns, moons, planets,
All distances of place however wide,
All distances of time, all inanimate forms,
All souls, all living bodies though they be ever so different, or in different worlds,
All gaseous, watery, vegetable, mineral processes, the fishes, the brutes,
All nations, colors, barbarisms, civilizations, languages,
All identities that have existed or may exist on this globe, or any globe,
All lives and deaths, all of the past, present, future,
This vast similitude spans them, and always has spann'd,
And shall forever span them and compactly hold and enclose them.

WALT WHITMAN

Commentary:

Satellites for Oceanography — The Promises and the Realities

by Richard Goody

The promises are of a revolution in many branches of oceanography, a three-dimensional view of the world ocean (two horizontal and one of time), data sets for synoptic studies in biological, geological, and physical oceanography and some important, novel information such as sea-surface topography, maps of surface wind stress, identification of frontal systems, and so on. The realities are that these data are not ready to be assimilated into oceanographic research, that they are difficult to comprehend (problems of tape format, calibration, image processing) and even to obtain, that they are of limited value taken in isolation, and that progress requires a commitment from leading oceanographers for whom there may be little motivation.

As an outsider looking in, I might hesitate to offer an opinion on such a complex situation except that I have seen most of it before. In the 1960s, remote sensing became a part of modern meteorology; in the 1970s astronomy started to be affected by the operational problems of space research; and, more recently, remote sensing has started to dominate some aspects of cryospheric research, particularly respecting sea ice. Space techniques have not been equally productive in all areas. After 20 years some benefits may accrue to meteorology, but up to a year or two ago skepticism as to the value of space data was widespread and justified. For astronomy, space research has opened entirely new areas in high-energy astrophysics and offers major improvements in other fields. For studies of sea ice, the adjective revolutionary may prove to be appropriate.

In the perspective of these other sciences, the prospects for oceanography may be closer to those for cryospheric research than meteorology, principally because the data provided by satellites have some really novel aspects. These prospects will, however, remain no more than prospects until the data are brought to bear on major oceanographic problems. Once this has been done a few times the scientific community will understand in concrete terms how to use the data. Meanwhile, the hard preliminary work will have been done to make the data accessible in useful form at the research level. In this sense, the introduction of satellites does not differ from any

Page opposite, a computer-assembled two-image mosaic of Saturn's rings, taken by NASA's Voyager 1 on Nov. 6, 1980, at a range of 8 million kilometers. (Photo courtesy of NASA) other technical revolution in the earth sciences. Even with a continuing effort, the full utilization of new methods typically takes a decade or so: a research "generation" is needed to bring in a new group of younger workers.

The new methods should more accurately be described as remote sensing, which title also includes acoustic tomography, radiometry, and laser sounding from ships and aircraft. Methodologically, however, satellite measurements differ because they introduce a new type of vehicle, and that step is more important than may appear at first sight. From the scientific point of view, satellites open up the possibility of investigating on a very large scale, up to and including global scale. At the same time, satellite measurements cannot be assimilated by a gradual step-by-step evolution from ship and aircraft measurements. When a satellite is flown, it introduces an overwhelmingly large new data stream, difficult to grapple with and outside the control of individual investigators. The cost of the missions and their visibility are such that they command the attention of Congress and the public. This places unfamiliar pressures on the scientific community and new opportunities that can either arouse enthusiasm or resentment, but with which we must come to terms. These factors cause research with satellites to differ so greatly from its precursors that it requires special approaches, and I shall confine my remarks to this topic.

An accurate data set can usually be obtained but it will probably be incomplete.

Articles in this issue of *Oceanus* will make more clear what the opportunities for oceanography really are, but I would like to summarize them. The Coastal Zone Color Scanner is a sophisticated color camera with which spectacular pictures have been obtained. They are extensively processed to bring out certain features, such as chlorophyll concentrations.

Another familiar instrument is the infrared sounder, which can record the thermal radiation emitted by the sea surface and can be interpreted in terms of surface temperatures. Many readers have seen the thermal images of the Gulf Stream flowing up the coast of Florida. For some purposes — for example, detection of ecologically interesting features, such as warm rings — these qualitative images are useful, but the problem of obtaining sea-surface temperatures accurate enough for physical investigations is not yet satisfactorily solved. This question offers an instructive diversion because it is illustrative of a class.

Satellites can obtain radiometric temperatures from either infrared or microwave signals. This radiation originates from the upper microns or, at most, the upper millimeter or two of the ocean. Ship measurements, on the other hand, give a mean temperature in the uppermost meter or two. Bucket and radiation temperatures will necessarily differ because they sample different thermal regimes. The task is to understand this temperature difference, possibly to predict it, and to use each temperature where it is most appropriate. Radiation temperature, for example, is the appropriate temperature for some aspects of air-sea interaction studies.

Another question raised about radiation temperatures relates to the effects on the measured radiation of atmospheric absorption and emission and the state of the sea surface. There is every indication that we can differentiate conditions when these factors interfere with temperature measurements from those when they are insignificant. An accurate data set can usually be obtained but it will probably be incomplete. The important question is: how much does this lack of completeness interfere with research objectives?

Such a question cannot be considered in the abstract. There is no sense in asking: which are better — bucket or satellite temperatures? Value can be judged only with respect to an operational or scientific question, for example: which is most valuable for climate prediction? Answers to this kind of question will not be forthcoming without the expenditure of effort by capable investigators.

Other important remote-sensing instruments were flown on the short-lived Seasat satellite which gave data from June to October 1978 (a series of articles on Seasat instruments appeared in *Oceanic Engineering, OE-5,* No. 2, April 1980). In addition to infrared and microwave radiometers (which are passive, that is, they depend on emission from the ocean surface), there was an active radar scatterometer that could measure the return signal scattered from surface capillary waves. From the scatterometer data it has proved possible to infer surface wind stress and wind velocity both in magnitude and, with an acceptable indeterminacy, in direction. Data now exist that can resolve any questions relating to the coupling between wind stresses and ocean currents.

Interest in radar altimeters has grown rapidly since the flight of Geos-3 in 1975. The desired accuracy for oceanographic purposes is generally somewhat less than 10 centimeters, and under certain circumstances this may be achieved. This provides a unique measurement of one aspect of the driving forces for deep currents (see page 17). A combination of measurements from hydrographic stations and satellites now provides the novel opportunity to define the fundamental pressure driving force in the oceans.

Finally, the most spectacular of all Seasat instruments, the synthetic aperture radar (SAR), imaged sea-surface conditions with a resolution of about 25 meters. Despite the novelty of the SAR images and the variety of events they appear to portray, they have had little impact on most branches of oceanographic research. Possibly this is an idea whose time has not yet come, but the instrument and the methods of reduction will probably continue to be developed for studies of sea ice, for which purpose SAR promises to be a very powerful tool.

Does money put into satellites mean less money for ships?

The effort to understand Seasat data gave rise to field experiments and an active data analysis program. Slowly, a picture is forming of the possibilities of remote sensing. As it does so, one point bears frequent reemphasis: virtually no remote-sensing measurement can stand alone without support from in-situ measurements. In general, remote-sensing techniques do a remarkable job of two-dimensional mapping but have little depth penetration. This objection may be partially overcome if enough effort is invested: for example, there are features in SAR that are probably related to events taking place below the surface, but just what is happening and how the data can be interpreted in terms of events at depth are not known. If oceanographic science is to profit to a maximum, planning must start for combinations of measurements from satellites, aircraft, buoys, ships, and islands. Buoys and satellites should be planned as joint systems and satellites can be used to read out information from global buoy networks. Since we have hardly started to assimilate any satellite data into modern oceanographic research, this requires thinking far ahead, but the lead times are so long and the costs are so great that the task cannot be avoided. There are those who may hesitate at this point. Does money put into satellites mean less money for ships? The budgetary practices of the federal government and the complexities of interagency operations are such that the question is unanswerable. It is even possible that satellite research may lead to increased funding for ships. Without a much better understanding of the political process than most of us possess, scientists should do what they do best: fashion the satellite into the most effective tool possible for oceanographic research.

Style is important, particularly if the aim is to influence such doggedly independent people as research oceanographers. During the 1970s, the thought often went through my mind as to what it would do to astronomers if their research involved less access to their lovely mountain observatories and the aesthetically pleasing process of telescopic measurements. How might they fare shut up in a windowless city block tied up with endless computer tapes? Of course, things do not have to be that bad. Half a century ago, L.F. Richardson suggested that numerical weather prediction should take place at an institute set in idyllic surroundings so that "those who compute the weather should breathe of it freely." But many oceanographers are motivated by a love of the ocean environment, and satellites certainly will not increase their opportunity to go to sea.

Another aspect of style involves the different people in such widely different activities as ships and space. The typical oceanographer may not be prepared for the focused project, strong project managers, and the large centers that contribute to the National Aeronautic and Space Administration's (NASA's) success. NASA will, however, be the dominant force in the use of satellites for oceanography for some time to come. Unlike the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Navy, NASA has no mission in ocean science. Its concern is with innovative space systems and piloting new projects through the intricacies of the Space Act. Oceanographers may find this difficult to understand, although NASA has developed excellent approaches for working with scientific communities. Each must adapt to the other, however, which can take time.

It is difficult to be neutral about new space projects: they are too expensive, involve too much effort, and often have a revolutionary impact on their area. I have offered a positive view based on the evidence available from oceanography as well as from other fields. It is my impression that remote-sensing techniques from satellites are here to stay as an oceanographic tool. I doubt whether there will be any important changes in instrumentation during this century. There will be improvements, but the main task will be understanding and using existing equipment. Important questions remain as to which satellite systems will be flown, how the data will get to the scientific community in useful form, how satellite and in-situ measurements can be related, how the work is to be funded, and so on. All such questions can be answered well or badly but they can only be answered really well if creative oceanographers invest time and effort into them. The opportunity is important and it should be grasped, cautiously to be sure, by at least some of the oceanographic community.

Richard Goody is Mallinckrodt Professor of Planetary Physics in the Division of Applied Sciences at Harvard University, Cambridge, Massachusetts.

From Antiquity Onward

(Photo by Jan Hahn)

by Gifford C. Ewing

Who can tell when remote sensing of the oceans was initiated? The beginnings are irretrievably lost in antiquity. By the time of Homer, reference to the "wine dark sea" was already in the vernacular and the twin vortices of Scylla and Charybdis were familiar to Odysseus. No doubt Phoenician and Greek sailors had learned to decipher many secrets of the sea from vantage points aloft. So, if we recognize that "remote" is a relative term, we will understand that the art of remote sensing did not spring into being all of a piece in a flash of creation but rather emerged gradually over centuries with the accumulated experience of sailors. In fact, we see that remote sensing is in some ways more characteristic than proximate sensing, which is limited to observations made by immediate contact, as in thermal thermometry. Most determinations of a physical state are made at some distance by acoustic or visual means through intervening water or air, so we must conclude that remote sensing is neither new nor unfamiliar and that it has a long history of continuous development without a recognizable beginning.

Nevertheless, we have an intuitive sense of innovation that has to do with rates of advance and with turning points where change is either accelerated or retarded. To identify such a turning point in current times, we must look for particular circumstances that may be shown to have generated the perception of novelty justifying the designation of the start of space oceanography as something set apart from previous technology.

An earlier radical change was made by the *Challenger* expedition in the late 18th century when for the first time the high seas came under systematic scientific scrutiny. In the decades following the expedition, oceanographic understanding was fed by spot sampling that was discontinuous in space and time. Many charts were published with juxtaposed observations collected decades apart and by widely different techniques. Informative as these data were, they showed only the more stable characteristics of the sea and, by today's standards, were somewhat simplistic.

A major turning point was made during and after World War II with the impact of new technology and the ready availability of aircraft. For the first time, it became practicable to scan broad areas of the ocean in a quasi-simultaneous way that matched its geometry. For the world ocean is a thin sheet roughly similar to an extended newspaper page — that is, with horizontal dimensions some 3,000 times greater than its thickness.

This altered perception has already had a very fundamental impact on oceanography and will have far more in the future. To be sure, the extended view of the ocean surface is limited by obvious constraints because of the opacity of water and the overlying atmosphere. To a degree, these limitations can be overcome. Thus Iselin showed long ago that the vertical stratification of the central and upper oceanic layers is a homologous replica of the horizontal distribution of the variables in the surface layer where these water types are generated. Furthermore, many underwater phenomena, such as internal waves, have easily discernible surface consequences, such as bands of slicks and roughness. More fundamentally, the upper sunlit layers of the sea make up the regions through which nearly all energy transfers occur and where the most dramatic changes take place. Fortunately, this layer is readily accessible to observations from overhead and consequently to remote sensing. Progress in exploiting this capability was spectacular in the period after World War II. Thus in 1940, Kettering observed (from a hotel window in Miami Beach) cold steamer wakes in Gulf Stream water by means of an infrared radiometer; Clark took the next step at the Naval Research Laboratory by observing persistent thermal wakes from a blimp. Similarly, Wilkerson, by means of an airborne radiometer, followed the annual advance of warm ocean water to Iceland and was able to forecast the failure of the fishery there when the advance became stalled. At Woods Hole, in 1955, Richardson, Von Arx, Stommel, Jones, and Gingrass tracked the Gulf Stream for many miles with an airborne Golay radiometer. In 1956, Hardy was able to chart from the air the boundary between the Irish Sea and the English Channel by the color differences related to the abundance of salp in the Irish Sea. In 1961, Strickland mapped color contrasts in upwelling light over the Georgia Straits using an airborne spectrophotometer and fiber optics to compare the upwelling and the incident light. In 1963, McAlister and McLeish used a two-wavelength airborne radiometer to measure the flux of heat through the sea surface.

Because there was such success with low-level, limited surveillance from aircraft, it followed quite naturally that the advent of earth-orbiting and sun-synchronous satellites would give a strong boost to space oceanography. It was correctly surmised that, since most atmospheric absorption takes place in the lower, denser layers of the atmosphere, hyper-altitude observations would not suffer irreparably in comparison with those from aircraft. So, at last, the possibility of extended ocean coverage continuous in either space or time was realized. With the increased effectiveness and resolution of remote-sensing instruments came the ability to see details of mesoscale oceanic phenomena and their evanescent changes. It was in response to these enormously enlarged possibilities that NASA, under the leadership of Badgley, undertook the development of a program in oceanography. At his request in 1964, the Woods Hole Oceanographic Institution invited a group of 143 scientists to participate in a five-day colloquium on space oceanography. This meeting led to several more in the succeeding 16 years, the most recent of which was convoked in Venice in 1980. The latter conference showed that progress has been made on all the fronts perceived in 1964. The tangible results are to be seen in the Seasat satellite program, the Coastal Zone Color Scanner, and lastly, the satellite remote-sensing facility at the Scripps Institution of Oceanography in La Jolla, California. Oceanography from space has finally arrived. By means of the radio data received from orbiting and stationary satellites, it is now possible to monitor extended distant ocean areas semi-continuously, to place instrumented buoys or to vector vessels efficiently to critical centers of interest, and to examine these centers in relation to their surroundings.

It is now timely to consider what might be undertaken in the new decade. We might well shift our primary concern from the comparison between ground truth and space truth to purely space projects that can now be investigated in their own right. As an example, we may seek to measure the coherence of oceanic events over extended space and time.

Thanks to modern technology and the many fresh minds that are focusing on the world ocean, we can and must welcome innovation and ask new questions of the sea. To the extent that we can stretch our imaginations, we shall be able to take another major step in the quest of an enlarged understanding of the only spinning hydrosphere within our ken.

Gifford C. Ewing is a Scientist Emeritus at the Woods Hole Oceanographic Institution.

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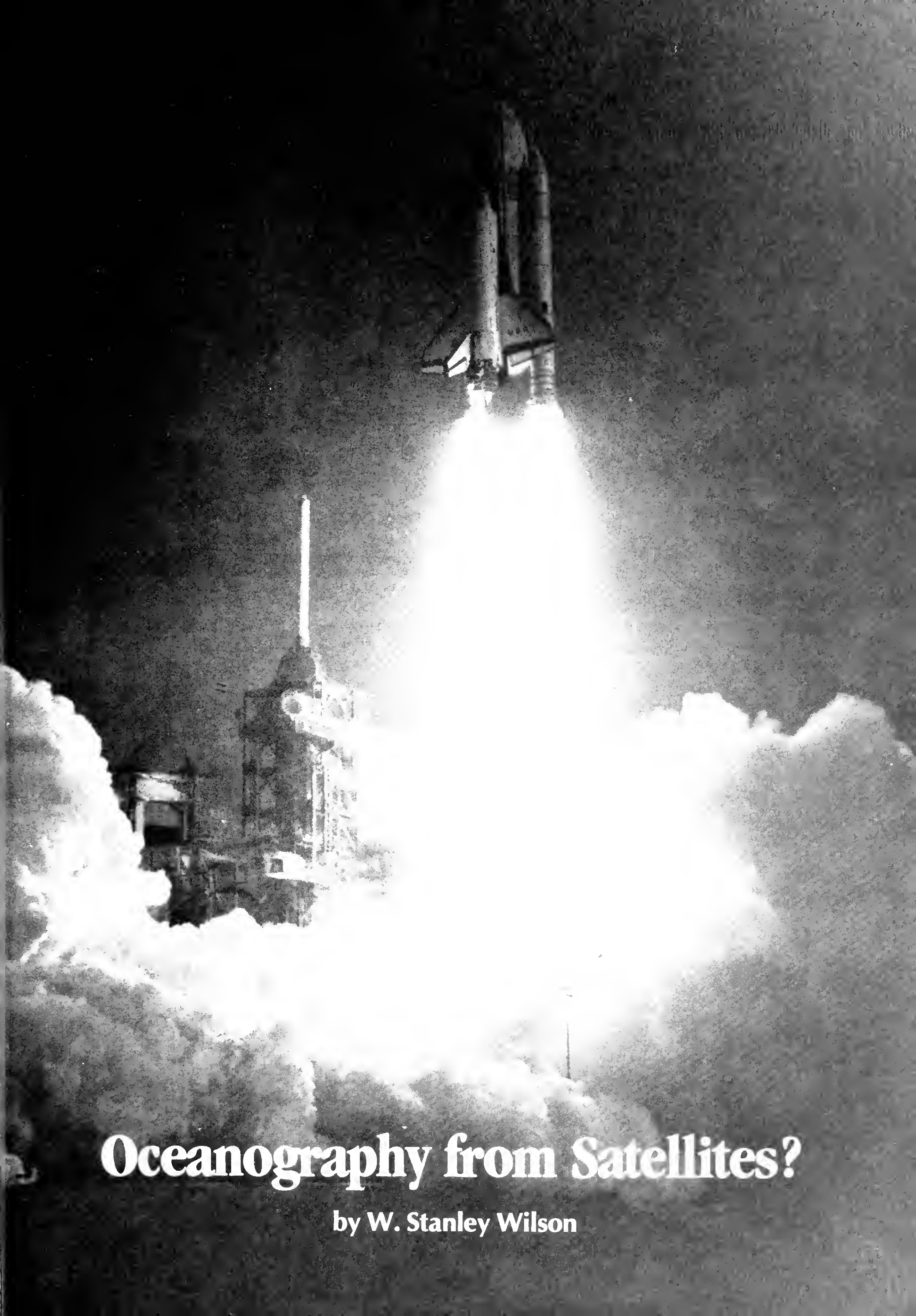

Oceanography from Satellites?

by W. Stanley Wilson

The space program has had a profound, if not revolutionary, impact on a variety of fields since the launch of the first satellite, Sputnik I, almost a quarter of a century ago. In astrophysics, the study of the physics of celestial bodies, observations made from the earth's surface have been restricted to those limited portions of the electromagnetic spectrum (visible and some radio frequencies) not filtered out or blurred by the atmosphere and ionosphere. By being able to make observations above the atmosphere and ionosphere via satellites, we have discovered many previously unknown aspects of the universe.*

One such aspect was revealed by the Solar Maximum Mission, an earth-orbiting spacecraft launched in 1980 that studied the sun. We discovered that the solar constant (the total amount of solar energy reaching the earth) is not "constant," but rather constantly fluctuating from a few hundredths to a tenth of a percent, twice dipping by 0.2 percent for a week-long period during which there was considerable increase in sunspot activity. Although these shorter-period fluctuations are probably inconsequential, longer-period ones are definitely not. Understanding them is potentially important because the circulation of the atmosphere and the oceans, as well as the extent of the polar ice caps (all of which are ultimately "driven" by solar energy), could themselves respond to longer-period fluctuations and change in ways that could greatly affect our climate.

In planetology, the study of planets in our solar system, spacecraft have allowed observations to be made during flybys of other planets; observations have even been made down through the atmosphere and on the surface of both Mars and Venus. This capability has enabled the field of comparative planetology to mushroom, providing otherwise unattainable information on the evolution of our solar system and characteristics of each planet from Mercury out to Saturn. If the Voyager flyby of Uranus in 1986 is successful, it too will be included (see Figures 1, 2, and 3).

We have found that the atmosphere of Venus consists primarily of carbon dioxide, which acts as an insulating blanket retarding the release of heat from the planet's surface. This effect, known as the greenhouse effect, can easily account for its unusually high surface temperature of 480 degrees Celsius. Understanding the heat balance of Venus has given us a greater appreciation of the heat balance on earth. This knowledge will help us assess the critical problem of carbon dioxide buildup in the atmosphere and a possible increasing greenhouse effect that results from continued burning of fossil fuels (see page 48).

Figure 1. The surface of Mars. Photograph taken by the Viking I Lander in August 1974; the 3- to 4-degree elevation angle of the sun accentuates the surface characteristics; rocks just above the middle of the picture are 1-foot across. (Photo courtesy of NASA)

As the demand for capacity has increased in the communications field, geosynchronous satellites have been developed to relay messages. A geosynchronous satellite rotates about the earth in the earth's equatorial plane; its rotation rate equals the rate at which the earth rotates about its own axis. This satellite thus remains fixed relative to the earth at some point above the equator. Geosynchronous satellites have proved to be a cost-effective alternative to the installation of land lines and microwave relay towers for long-distance, high-volume routes, and they are especially well suited for underdeveloped nations where there are a number of isolated, low-volume areas to be interconnected. Not surprisingly, private enterprise now dominates this field; there are more than 60 commercial communications satellites in use worldwide today.

In navigation, satellites have provided an accurate, global, all-weather position-fixing capability that is especially useful to ships at sea. In this case, the satellite navigator uses a knowledge of the satellite's position (just as a celestial navigator uses celestial bodies) to locate his own position. Because tracking can be done by radio in any

Overleaf, the space shuttle Columbia rises off the launching pad at the Kennedy Space Center in Florida on April 12, 1981. (Photo courtesy of NASA)

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*Jastrow, 1979, presents a fascinating account of our present understanding of the universe, much of which has been based on results of the space program. Newell, 1980, gives a candid and illuminating history of NASA.

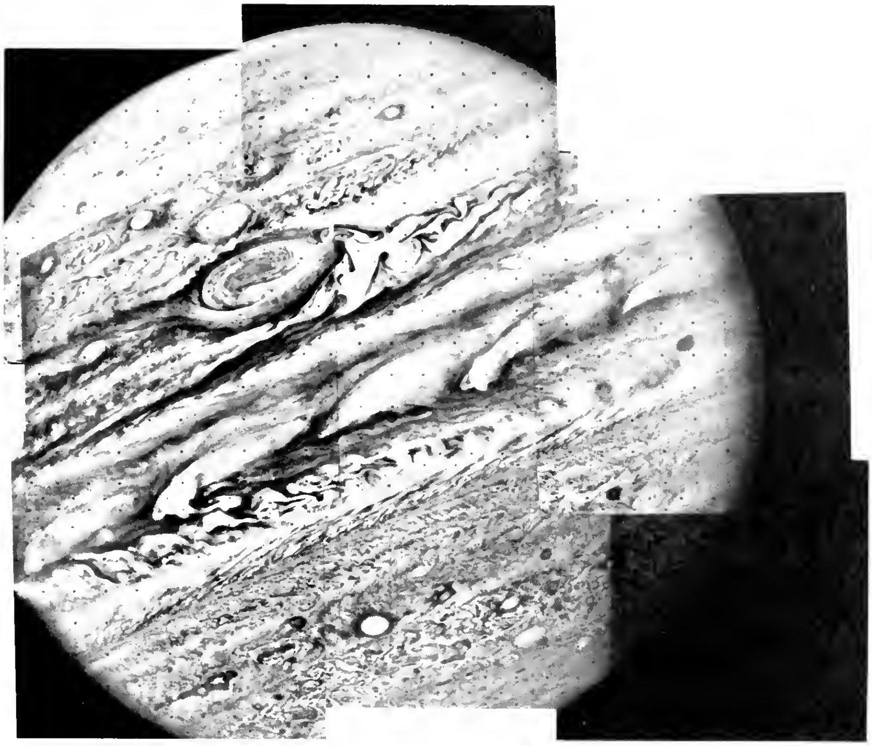

Figure 2. Jupiter as seen by the Voyager 1 spacecraft in March 1979. The mosaic was assembled from nine individual pictures taken at a distance of 4.7 million miles; distortion is caused by rotation of the planet during the 96-second intervals between individual pictures; the large circular feature just above and to the left of the center is the Great Red Spot — a permanent "hurricane" whose diameter is equivalent to three earth diameters. (Photo courtesy of NASA)

Figure 3. Saturn and its rings as seen by the Voyager I spacecraft in November 1980; the picture, taken at a distance of 3.3 million miles, was shot after the spacecraft passed Saturn, revealing the shadow of the Sun on its rings. (Photo courtesy of NASA)

weather, satellites can be used whenever they are above the horizon. Transit is a U.S. Navy system in use since 1963, nominally employing five satellites. It provides global position-fixing good to about 40 meters, with fixes available every hour or two. (Although there are shore-based radio systems that provide continuous position-fixing, they either are limited to coastal areas or provide fixes good only to about 3 kilometers). As an example of their popularity, Transit navigation sets in use today number more than 16,000. The Global Positioning System (GPS or Navstar) is a Defense Department system in trial use with four satellites; full operation (using 18 satellites) is proposed for 1987. It will provide global position-fixing good to *better than 10 meters continuously.* Because of its military potential, it is not clear how much of this capability will be freely accessible.

In meteorology, two geosynchronous and two polar-orbiting satellites routinely provide observations of the earth's atmosphere for the National Weather Service to use in deriving and verifying forecasts. (And there are also two similar polar-orbiting satellites used by the Defense Meteorological Satellite Program.) These satellites can provide not only images of cloud patterns that are closely associated with fronts and high- and low-pressure systems (Figure 4) but also estimates of vertical atmospheric profiles of temperature, humidity, and in certain instances, wind velocity. Their capability to detect and track *every* hurricane in the region extending from the mid-Pacific to the mid-Atlantic has been invaluable. By providing observations over otherwise data-sparse regions, such as the eastern North Pacific Ocean — an area from which weather patterns generally drift toward the United States — they have significantly improved the accuracy of the 1- to 3-day forecasts for the western half of the United States.

Traditional Oceanography

Now let us look at oceanography. Following centuries-old seafaring traditions, oceanographers have gone to sea in ships to make their observations. They have traditionally worked in small teams led by a principal investigator, who essentially has complete control over his instrument development, its deployment at sea, and subsequent data analysis ashore. This scale of manpower is quite the opposite of that employed in space activities, where a seemingly enormous team of rocket, spacecraft, sensor, telemetry, and data-system experts is required, as well as many principal investigators. On the other hand, both the sea-going and space teams must build instrumentation suitable for unattended operation in a hostile environment for long periods of time.

Since the sea is relatively accessible by ship and amenable to study through traditional techniques, oceanographers initially had little motivation to exploit space techniques for observing the ocean, in contrast to the astrophysics and planetary communities. Within the last decade or so, however, there has been a growing appreciation of the complexity of the sea and the limitations posed by traditional techniques of observation.

For example, oceanographers have confirmed that the oceans, like the atmosphere, have "weather" (oceanic analogues to atmospheric high- and low-pressure systems — Warren and Wunsch, 1981). They recognize the interplay between surface winds, ocean currents, upwelling nutrients, and the resulting biological productivity (Richards, 1981). Their polar colleagues are learning how the ice pack responds to surface winds and ocean currents (Pritchard, 1980). There is a general recognition that observations need to be made simultaneously over broad regions of the ocean, observations that are needed to complement ship observations, yet cannot be made from ships. This type of observation is called synoptic, and an example is the infrared surface temperature image of the Gulf Stream system (see front cover). There also is the recognition that satellites have a capability to make such synoptic observations — subject to the fundamental limitation that they can *only* sense conditions at or near the surface of the sea, because of the severe attenuation of electromagnetic signals in water.

Oceanographers have benefited from the space program, but primarily through the increased efficiency of ship operations. For example, the Transit navigation system has enabled them to make more detailed maps of sea-floor properties and to more accurately locate moored subsurface instrumentation (thus helping ensure its subsequent recovery). Ship-to-shore communications and improved marine weather forecasts are other examples. Satellites have been used as platforms to track drifting buoys so that surface currents can be inferred and, in a few instances, satellite-derived sea-surface temperature or color images have been used to plan a ship's cruise track. However, all in all, the space program has had neither a profound nor revolutionary impact on oceanography as it has on the other fields previously mentioned. To see how far we have progressed, though, let us look at the satellite sensors used to observe the oceans.

Satellite Observations

The first satellite observations of the oceans were made visually and photographically by the astronauts in the Mercury program almost two decades ago. Satellite ocean sensors have evolved from the infrared radiometers on the early meteorological satellites, to the first microwave instrument on Skylab in 1973, to the suite of microwave sensors on Seasat, and finally to those still flying today on Nimbus-7 and the Goes/NOAA (National Oceanic and Atmospheric Administration) series of satellites (Table 1). A brief description of these sensors follows; Stewart's article in this issue (see page 66) discusses them in more detail.

Altimeter *—a pencil beam microwave radar that measures the distance between the spacecraft and the earth. Measurements yield the topography and roughness of the sea surface, from which the geostrophic (or density-driven) current and average wave height can be estimated.*

Color Scanner *—a radiometer that measures the intensity of radiation emitted from the sea in the visible- and near-infrared bands in a broad swath beneath the spacecraft. Measurements yield ocean color, from which chlorophyll concentration and the location of sediment-laden waters can be estimated.*

Data Collection System (DCS) *—a radio receiver/transmitter that receives data automatically transmitted from sensors deployed on unattended platforms (for example, small islands or moored buoys) and relays them back down to a central receiving station. This system is in place both on the geostationary satellite series, Goes, and on the polar-orbiting series, NOAA; in addition on the NOAA series, the DCS also locates the position of the platform (for example, drifting buoy) upon which the sensors are mounted.*

Figure 4. Cloud patterns on the earth as seen by NOAA's Goes East satellite on August 8, 1980. Hurricane Allen is seen dominating the Gulf of Mexico, and Hurricane Isis is seen off the west coast of Mexico. Note the simplicity of weather patterns across the United States — barely a cloud overhead anywhere — as the nation suffered through a prolonged heat spell. (Photo courtesy of NASA)

Table 1. Selected groups of civilian spacecraft launched by NASA from 1959 to 1980.

Purpose	Spacecraft Names	Sponsor (If not NASA)	Launches (No. Successful/ Total)	(Years)
Astrophysics	Explorer, Orbiting Observatories		60/74	1961-1980
Planetary	Pioneer, Mariner, Viking, Voyager		20/24	1962-1978
Communications — R&D	Echo, Relay, Syncom, Ats		13/16	1960-1974
Operational	Intelsat, Westar, etc.	Commercial	39/43	1962-1980
Meteorology — R&D	Tiros, Nimbus, Sms (1)		22/24	1959-1978
Operational	Itos, Goes, NOAA (2)	NOAA	19/22	1966-1980
Geodesy	Explorer, Pageos, Geos, Lageos (3)		7/7	1964-1976
Terrestrial	Erts, Landsat		3/3	1972-1978
Oceanography	Seasat (4)		1/1	1978

(1), (2), (3) also benefit Oceanography:

Spacecraft	Sensor
(1) Tiros-N	DCS, IR
Nimbus-5	MR
Nimbus-6	DCS, MR
Nimbus-7	CS, MR
Sms	DCS
(2) Goes Series	DCS
NOAA Series	DCS, IR
(3) Geos-3	ALT

(4) Seasat sensor complement:
ALT, IR, MR, SAR, SCAT

Sensor Key

ALT	Altimeter
CS	Color Scanner
DCS	Data Collection System
IR	Infrared Radiometer
MR	Microwave Radiometer
SAR	Synthetic Aperture Radar
SCAT	Scatterometer

Infrared Radiometer *— a radiometer that measures the intensity of radiation emitted from the sea in the infrared band in a broad swath beneath the spacecraft. Measurements yield estimates of sea-surface temperature.*

Microwave Radiometer *— a radiometer that measures the intensity of radiation emitted from the sea in the microwave band in a broad swath beneath the spacecraft. Measurements yield microwave brightness temperatures, from which wind speed, water vapor, rain rate, sea-surface temperature, and ice cover can be estimated.*

Scatterometer *— a microwave radar that measures the roughness of the sea surface in a broad swath on either side of the spacecraft with a spatial resolution of 25 to 50 kilometers. Measurements yield information on short surface waves that are approximately in equilibrium with the local wind and from which the surface wind velocity can be estimated.*

Synthetic Aperture Radar (SAR) *— a microwave radar similar to the scatterometer except that it electronically synthesizes the equivalent of an antenna large enough to achieve a spatial resolution of 25 meters. Measurements yield information on features (swells, internal waves, rain, current boundaries, and so on) that modulate the amplitude of the short surface waves; they also yield information on the position and character of sea ice from which, with successive views, the velocity of ice floes can be estimated.*

The most significant problem in deploying these sensors in space has been associated with data handling: the total quantity of data and the associated acquisition rates are some orders of *magnitude* larger than those traditionally encountered in oceanography.* Considerable attention must be given to the development and refinement of algorithms (the procedures for conversion of raw data coming from satellite sensors into a form expressed in geophysical units and useful to oceanographers), as well as to the provision of dedicated computing systems upon which the algorithms are applied to the satellite data. Seasat and Nimbus-7 were both launched three years ago; because of technical difficulties Seasat only lived three months, whereas Nimbus-7 continues performing today, well in excess of its one-year design life. At the present time, the bulk of the Seasat data has become available in geophysical units for use by the oceanographic community, and a significant amount of data from the ocean sensors on Nimbus-7 is becoming available. These delays in data availability are testimony to the enormity of this problem. Now that accurate algorithms are being developed, data systems for future sensors of similar design can be streamlined for near-real time applications, if necessary.

The deployment of ocean sensors in space and the subsequent data analysis and publication of results have demonstrated the *technical feasibility* of viewing the ocean from space. We are now addressing the *potential utility* of viewing the oceans from space. What can we expect from the space program if we use satellites deliberately and systematically to view the oceans? This is the main question considered in the articles in this issue. Wunsch examines how satellite altimetry can measure the topography of the sea surface, providing information on geostrophic circulation. O'Brien looks at how satellite scatterometry can determine wind stress at the sea surface, from which information on the wind-driven circulation can be gained. Esaias explores how satellite color observations can measure near-surface chlorophyll concentration, and thus supply data on primary productivity of the oceans. Weeks focuses on sea ice and how a variety of satellite techniques can be used to determine characteristics of the growth and movement of ice cover in polar regions. Bretherton views ways satellites can determine the interaction of the ocean with the atmosphere and its relation to changes in climate. Finally, Montgomery outlines how various satellite techniques can provide information of value to the operational oceanographic community, including those involved in commercial shipping, offshore petroleum, fisheries, and deep-sea mining.

We in the National Aeronautics and Space Administration (NASA) have taken a preliminary look at these needs and find that they fall into the following three general areas: 1) studying the circulation (both geostrophic and wind-driven components) and heat content of the oceans, and how they are influenced by the atmosphere, 2) studying the primary productivity of the oceans and how it is influenced by the physical/chemical environment and higher elements in the marine food chain, and 3) studying the growth and movement of sea ice and how they are influenced by the atmosphere and ocean.

Planning for the Future

Because there are potential near-term benefits in these areas, we are sponsoring a number of related studies. For example, we are looking at the definition of a dedicated altimetric satellite, Topex; the feasibility of flying a color scanner and a scatterometer as piggyback sensors on the NOAA operational meteorological satellites; and requirements via a bilateral Canadian-United States study for a dedicated SAR satellite, Firex (Table 2). We will be identifying requirements for in-situ observations and the adequacy of data collection systems to handle them. We have defined requirements for a dedicated polar satellite (Icex); completed a study defining a research complement to the recently terminated NOSS satellite program; and are informally discussing with both the Navy and NOAA, the operational ocean agencies, how these and other observations (such as microwave radiometry for determining sea-surface temperature) might be implemented and used to meet operational needs.

As these and other studies are completed, the greater American oceanographic community — including the academic, government, and commercial sectors — will be in a position to examine and establish priorities for both research and operational purposes, to look at how they relate to one another, and to develop a logical sequence of dedicated ocean spacecraft missions and/or piggyback deployments of ocean sensors on other spacecraft to meet these needs. Aspects that are sensitive from the national security point of view can be addressed accordingly.

We also will be in a position to relate U.S. plans with efforts under way in other nations. Japan presently has an ocean satellite under development, Mos-1, scheduled for launch in 1985; it will carry all passive sensors. The European Space Agency is in the final stages of authorizing funds for Ers-1, scheduled for launch in 1986 or 1987 — it will carry active and passive sensors. Canada is

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*As an example, the Coastal Zone Color Scanner currently flying on Nimbus-7 takes only 4 minutes to acquire the 182,000,000 bits of raw data needed for imaging a scene 1,500 kilometers square. This results in an average acquisition rate of 760,000 bits per second. A standard CTD (measuring Conductivity and Temperature versus Depth) used from a ship takes about 3 hours to acquire the 26,000,000 bits of raw data needed for a typical hydrographic station. This results in an average acquisition rate of 2,400 bits per second.

Table 2. Selected groups of potential future NASA spacecraft.

Purpose	Spacecraft Names	Acronym	Earliest Launch
Astrophysics	*8 Explorer-Class Satellites		1981-1987
	*Space Telescope		1985
	Origin of Plasmas in Earth's Neighborhood	OPEN	1987
	Gamma Ray Observatory	GRO	1988
	Advanced X-ray Astrophysics Facility	AXAF	1989
Planetary	*Galileo (Jupiter)		1985
	Halley Comet Flyby		1985
	Venus Orbiting Imaging Radar	VOIR	1988
Communications — R&D	30/20 GHz		1987
Meteorology — R&D	*Earth Radiation Budget Experiment	ERBE	1984
	Upper Atmospheric Research Satellite	UARS	1988
	NOAA Next & Goes Next		1989, 1990
Geodesy	Gravity Satellite (1)	GRAVSAT	1987
Terrestrial	*Landsat D & D′		1982, 1983
Oceanography	Topography Experiment	TOPEX	1987
	Free-flying Imaging Radar Experiment (2)	FIREX	1988

*These are the only spacecraft currently under development.

(1) Also benefits Oceanography.
(2) Also benefits Terrestrial.

interested in flying a SAR with another country in the late 1980s.

In concluding, we think that satellites capable of observing the oceans can lead to a dramatic breakthrough in our understanding of how the oceans behave as an overall system. Also, we think that this can result in more effective utilization of the oceans for civil and naval purposes. If this case can be adequately made by the greater oceanographic community, I believe oceanography from satellites has a good prospect for success.

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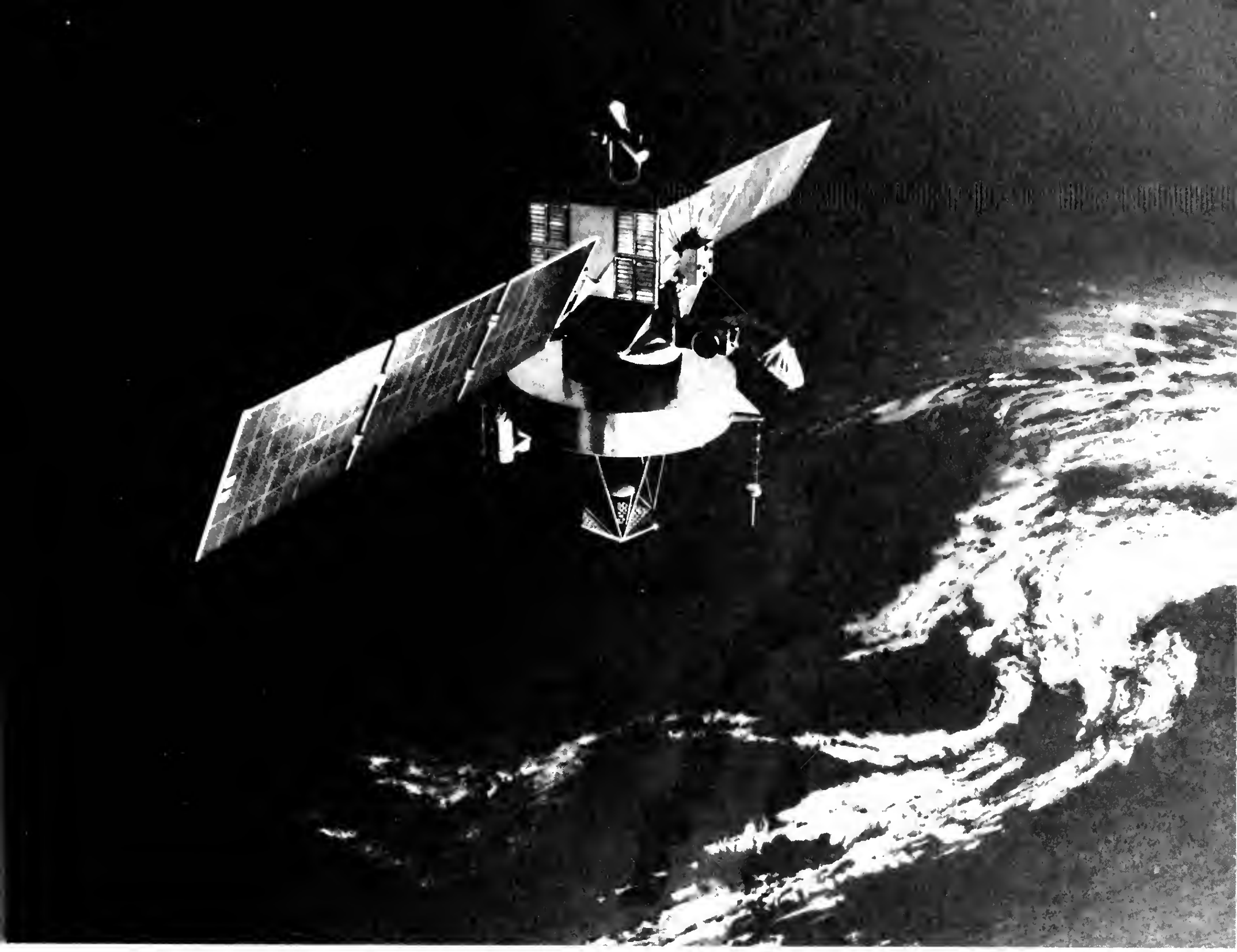


Artist's concept of Topex, an oceanographic satellite being proposed by NASA that would use radar altimetry techniques to globally measure the surface topography of the oceans. (Sketch courtesy of NASA)

The Promise of Satellite Altimetry

by Carl Wunsch

To understand a physical system, such as the ocean, we must first have a good description of its major characteristics. We can proceed to construct theories and models and test them against observations. The world oceans occupy an area of 360 million square kilometers and have a volume of about 1.46 billion cubic kilometers. As in any large fluid system, the ocean changes in complex ways from moment to moment and from place to place. A great variety of physical processes occur, ranging from phenomena like ripples, which occur on distances of millimeters or centimeters, to climatic fluctuations of the large-scale movement of water, involving the entire width of the Pacific Ocean.

Much of the study of these phenomena is most sensibly done locally. An oceanographer interested in the generation of waves by wind can choose some convenient piece of ocean and concentrate his resources there. The physics of wave generation in one location will provide insight into the same process in most other parts of the ocean.

But sometimes we want to be able to view the entire ocean basin, or perhaps the world ocean, at the same time. Consider, for example, what can loosely be called the general circulation of the ocean — the large-scale movement of water, which includes such phenomena as the Gulf Stream, the system of equatorial currents, and other massive flows of water persisting over long distances for long periods of time. Figure 1 is an impression (not very accurate) of the surface circulation of the North Atlantic Ocean.

There are many measurements suggesting that the Gulf Stream as it flows past Florida undergoes quite large fluctuations — up to 25 percent of its average value. If the amount of water going northward in the Stream is changed, the rest of the system, which returns the water southward, must also be changed by a similar amount. For a variety of reasons, including the important one of determining the climatic consequences of fluctuations in the amount of warm water flowing northward in the North Atlantic, we need to know where and how this changed flow manifests itself in the rest of the ocean basin — whether it be primarily at the eastern boundary, in a region immediately adjacent to the Gulf Stream itself, or distributed throughout the three-dimensional volume of the ocean. To answer such a question, we must observe the entire system.

Nonoceanographers are often surprised to discover that the ocean is unobserved. With a few notable exceptions, there are no routine reports on the conditions (temperatures, velocities, and so on) of the sea. Even though the ocean is a fluid that behaves very much like the atmosphere, oceanographers have no equivalent of the global network that reports the three-dimensional state of the atmosphere twice a day.

The reasons for this state of ignorance are as follows:

1) Radio waves do not propagate through the ocean, so we can neither "see" through it, nor send information through it the way meteorologists send back information about the atmosphere from balloon ascents.

2) The major tool for large-scale observation of the sea is the ship — a slow, expensive, labor-intensive, and often uncomfortable, instrument. An oceanographic vessel typically makes 10 to 12 knots. The reader may easily compute the time required to transit the Pacific Ocean once at this speed (a width on the order of 10,000 nautical miles) without stopping to make observations.

3) There has been no pressure to "forecast" the ocean like there has been to forecast the weather. Observations of the atmosphere are largely a by-product of the national government forecast services.

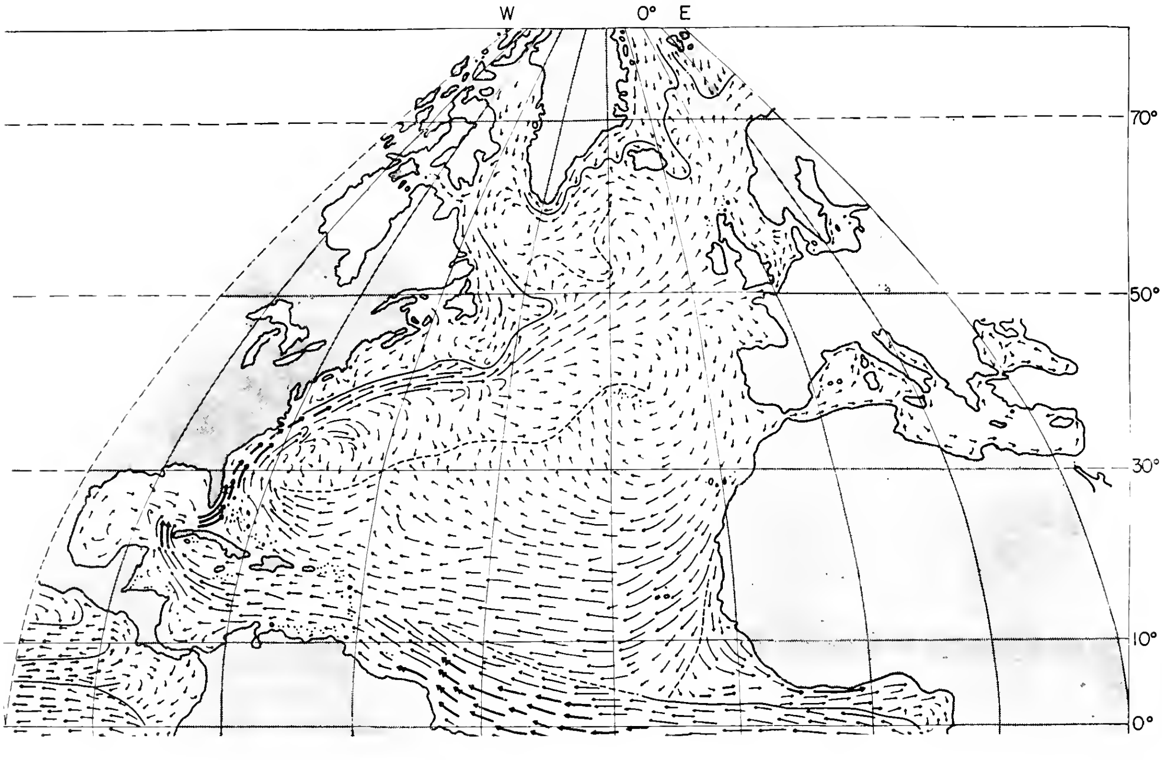


Figure 1. The supposed time average water velocity of the surface of the North Atlantic Ocean. Such charts are made from crude observations (principally the drift of ships) and can be regarded as qualitative information only. (From Defant, 1961)

But the need to observe the ocean is compelling. Understanding the large-scale movement of water and its changes is fundamental, not only to physical oceanography, but also to other branches of oceanography, and to meteorology. Some of the things we need to determine include: the transport of heat by the ocean and its contribution to controlling the climate of the earth; the uptake and mixing downward of chemical materials at the air-sea boundary, and the conditions controlling the chemical distribution of the ocean; why major fishing grounds occur in very special regions of the sea where there is a peculiarly fortunate mix of water movement and nutrient distribution; whether the seabed is a safe place to dispose of radioactive wastes; and where and at what rate sediments move on the sea floor. Because of the enormous volume of the ocean, remote sensing from space may prove to be the only effective way to obtain the necessary large-scale observations (there are some possibilities with acoustic remote sensing, too). To understand the kinds of measurement that would be useful, we must understand a little of the oceanographer's methods for determining water velocity.

Water Movement

Suppose that the water of the sea were not moving — that is, suppose that no external forces acted, except gravity, and the ocean came to rest. In observing water in a glass, we see that when the fluid is motionless in a gravitational field, its surface becomes perpendicular to local gravity. On a perfectly spherical earth that was not rotating, the shape of the resting sea surface would then be a perfect sphere. The earth's rotation makes the resting surface bulge out somewhat at the equator. In addition, the earth is not uniform at depth — it is, in fact, lumpy. This lumpiness makes the gravity field nonuniform over the surface of the earth. The shape that would be taken by a resting ocean on the earth is called the geoid (Figure 2). This figure illustrates the geoid relative to an underlying reference surface that is ellipsoidal in shape; the range of elevation changes is about 100 meters. Note the major low over Sri Lanka, a feature of considerable geophysical importance. A nonmoving sea surface would take on the shape shown in Figure 2, but superimposed on the overall ellipsoidal shape of the gross figure of the earth.

Let us now suppose that the wind starts to blow and the sea is set into motion. Let the water move in such a way that speed and direction of the water movement change slowly both geographically and in time. The two main forces acting on the moving sea, in addition to the wind, are gravity and the Coriolis force. The sea surface will get humped up relative to its resting position in one place, and will move down to compensate in

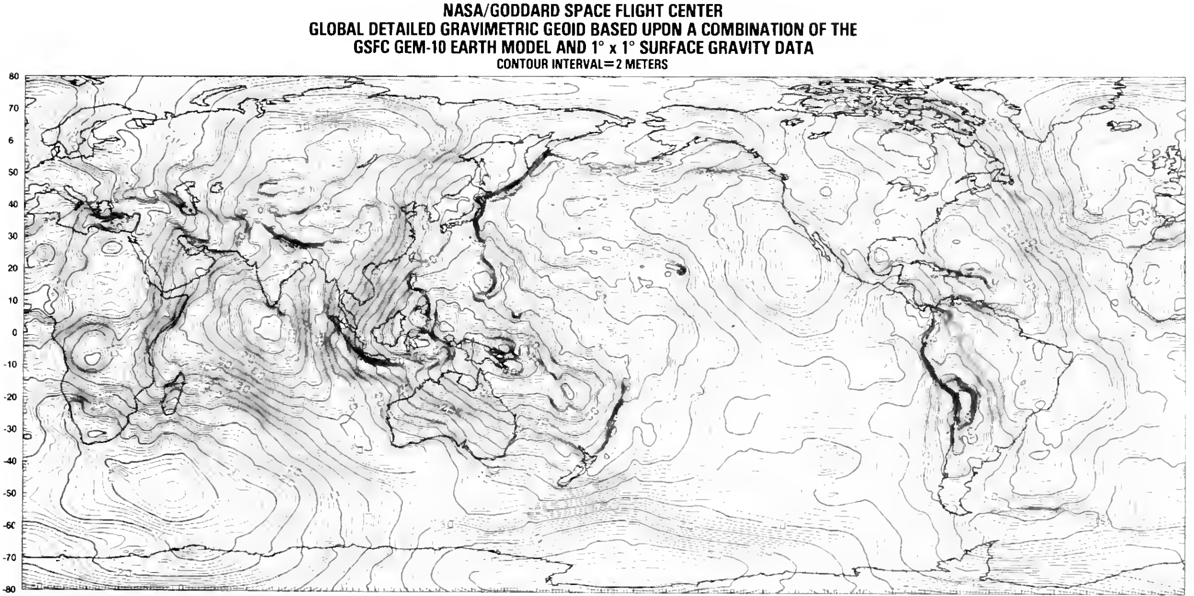


Figure 2. Estimate of the geoid — the shape of the surface of a resting ocean — as determined by scientists at NASA's Goddard Space Flight Center. Note the deep low south of India and that the total range (relative to an underlying smooth ellipsoidal surface) is more than 100 meters.

some other place (Figure 3). Gravity then will act to level the surface out again, as happens when water in a glass is set in motion. Where the sea surface is humped up or down, high or low pressures occur in the fluid.

The second force that is important for large-scale movement of the sea comes from the rotation of the earth, which gives rise to the Coriolis force. On a rotating earth in the northern hemisphere, a moving water parcel tends to be forced off to the right of its initial trajectory. In the southern hemisphere, the force acts to the left of the trajectory. If we combine the Coriolis force with the force of gravity, and demand that the two nearly balance, we have a special kind of motion called geostrophic. Instead of flowing from the regions where the water is heaped up to the regions where it has been removed to make a low, the water tends to flow around the highs and lows as in newspaper weather maps. Geostrophic motion is characteristic of geophysical fluids on the large scale. It means that fluid tends not to flow from high pressure to low pressure, but to move along lines of constant pressure.

Using Newton's laws of motion transformed into coordinates suitable for a rotating earth, we can compute the water velocity that results when the pressure forces are known. The pressure force could be found simply by measuring the distance between the geoid and the actual sea surface. The requirement that the pressure force and the Coriolis force be nearly in balance determines where and how fast the water is moving at the sea surface.

The idea is a very simple one, and was appreciated long ago, as far back as the turn of the century. But a practical difficulty arises which prevents its use. From directly measuring values of the water velocity in the sea, we know that the deviations of the sea surface from the geoid are in the range of 1 to 2 meters at most. These changes in elevation occur over distances of about 100 kilometers and longer. There has never been a way to measure such slight slopes directly. But it has been widely appreciated that if such surface maps could be constructed, oceanographers would be able to draw pictures much like those of meteorologists.

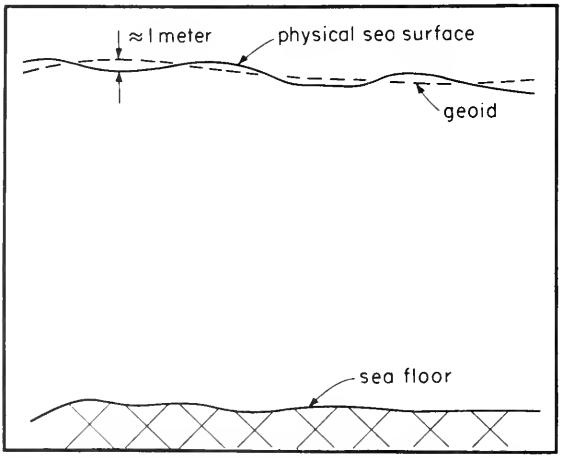


Figure 3. The sea surface relative to the geoid is bumpy but with a total range of only 1 or 2 meters. A measurement of the differences between the two surfaces would determine the pressure forces driving the surface flows of the ocean.

To understand why such maps would be so desirable to oceanographers, we must more closely examine the techniques that are used to measure the three-dimensional large-scale movement of water. The method was worked out by Scandinavian meteorologists in the early 1900s and is called the dynamic method. Its principles can be explained fairly easily. An oceanographer and his scientific party go to sea; at a chosen site (called a hydrographic station), they measure the temperature and salinity of the water from the surface to some depth. From these measurements, they can compute the density of the water, which is lowest at the top and increases downward. If the rotation rate of the earth and the acceleration of gravity are known, and if the geostrophic balance exists, they can — using the horizontal differences in density at two nearby hydrographic stations — compute the water velocity flowing perpendicular to the line connecting the two stations (Figure 4). But the water velocity so-computed changes with depth. In fact, this method does not really determine the water velocity, but only its value relative to its unknown value at the surface (or some other arbitrary reference depth). For want of adequate information, oceanographers have normally assumed that the velocity vanishes at depth in the ocean. The particular depth so-chosen is called a level-of-no-motion. Beginning as early as about 1920, oceanographers have constructed charts of water movement in the ocean based on density measurements and assumed levels-of-no-motion.

In the last 60 years or so, we have learned a great deal about water motion in the sea. Recently, it has been shown that there is a considerable variability in the movement of water at any given location. The ocean contains what is often called the mesoscale (synoptic scale) eddy field, or the mesoscale variability, which is similar to the weather seen in the atmosphere. Understanding the ocean requires an understanding not only of the time-average flow — the ocean climate — but also of the ocean weather.

Apart from the difficulties with the choice of ad hoc and unjustified levels-of-no-motion, oceanographers are faced with a formidable sampling problem. Given the expense of operating

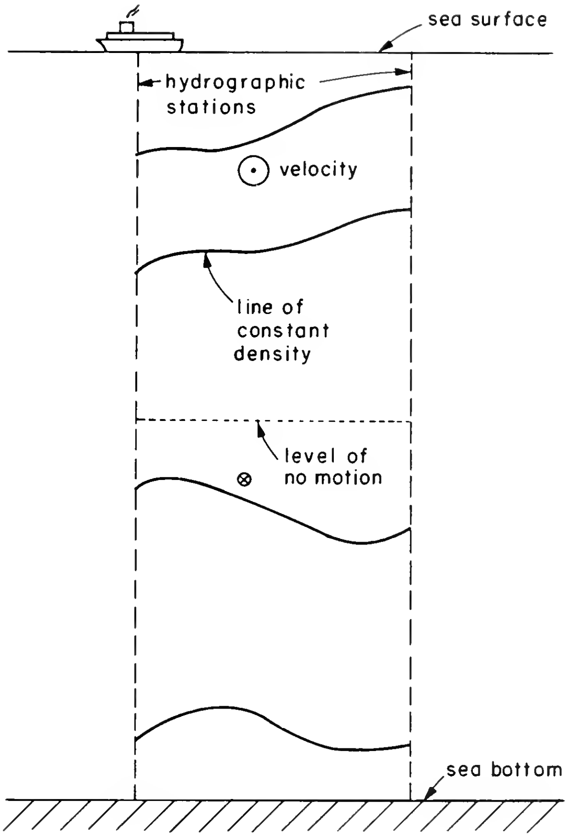


Figure 4. Oceanographers determine the relative water velocity at depth by measuring temperature and salinity from ships at two nearby hydrographic stations. (The very slight tilt of the sea surface is not shown here.) The velocity so determined requires an unknown constant that could be determined if the actual sea-surface slope were known. A level-of-no-motion is usually assumed instead.

ships, their slow speed, and the vast size of the oceans, it is not surprising to learn that the number of available hydrographic observations is inadequate for oceanographers trying to describe a changing global fluid. Because the ocean is changing all the time oceanographers are making their observations at sea, it is impossible to obtain a snapshot of the ocean at any moment in time. Such pictures of the state of the ocean are necessary if we are to understand how the ocean is working and whether it is evolving in time.

We might ask why the level-of-no-motion assumption could not be eliminated by directly measuring the water velocity at any depth in the ocean between two hydrographic stations. There are two problems with such a strategy. First, it takes many months or even years to average out the small-scale fluctuations that occur in a current meter record in the deep sea. This would require that a ship or mooring be left in place for extended periods of time. The second difficulty is that the number of instruments needed to define the velocity in the ocean is prohibitively large. Work of the last 10 years has shown that fluctuations in the ocean occur over distances on the order of 100 kilometers. To define the water velocity between North America and Europe would require about 60 such instruments along the line of latitude of interest. To define the world oceans on a 100-kilometer scale this way is beyond our resources. We need new tools.

Remote Sensing from Space

Some forms of satellite remote sensing of the ocean have been available for nearly 20 years. Most notable of these are the infrared maps of sea-surface temperature, which have been widely published (Figure 5). These maps show very complex patterns on the sea surface and have led to a good deal of speculation about physical processes. Sometimes such pictures have proved helpful in the interpretation of surface-based measurements of a more conventional type. In a few instances, the analysis of this form of data has led to the deduction that specific physical processes were occurring in the sea.

But on the whole, satellite infrared pictures of the sea surface and related measurements, such as that of ocean color, have not led to major advances in oceanography. Much of the oceanographic community has remained largely indifferent to them, and reasons for this general lack of acceptance of satellite oceanography are easy to trace. First, and most fundamental, the measurements are only of the thin upper skin of the ocean — determining temperatures characteristic of a depth of 1 millimeter or less. The surface of the sea is one of the most complex fluid dynamical situations occurring in nature. Air-sea interface physics involves a wide range of processes that transfer heat, moisture, and momentum back and forth between the atmosphere and the water. The spatial scales of these processes range in size from the microscopic (for example, the formation of foam and the ejection of salt into the atmosphere), on up to the thousands of kilometers characteristic of major atmospheric highs and lows. Determinants of sea-surface temperature involve a myriad of processes. Water upwelling from below can reduce the sea-surface temperature, as can high winds evaporating the sea surface. It has proved extremely difficult to interpret surface temperature patterns in the absence of direct supporting observations. Ocean color, which is also measurable at the sea surface, is complicated by complex biological processes in addition to the physical ones.

A second difficulty is that these measurements only have been possible when there are no clouds between the satellites and the sea surface. Clouds cover some of the most important

Figure 5. Infrared image of the sea surface. Such pictures show only a very thin upper skin of the ocean and can be obtained only in regions without cloud cover. (After Fofonoff, 1981)

oceanographic regions for significant periods of time (many of the most interesting regions have a greater than usual cloud cover because of the water temperature contrasts found there); this means that the view of the surface is intermittent at best.

Measurements of ocean color and temperature raise far more questions about the interpretation of the measurement than they have been able to answer. The oceanographer, otherwise armed with his conventional tools — ships, moorings, drifters — has had difficulty taking advantage of the information in these images.

Altimetry

The National Aeronautics and Space Administration (NASA) in a series of experiments, beginning with Skylab in 1974, and continuing with the Geos-3 satellite, and with Seasat in the autumn of 1978, has demonstrated the power of a novel form of remote sensing of the sea surface — satellite altimetry. A satellite is flown at about 1,000 kilometers above the surface of the earth (Figure 6). If the satellite carries an altimeter that can measure the distance from the spacecraft to the sea surface with an accuracy of a few centimeters, then by subtracting the one measurement from the other, we can find the shape of the sea surface. There are then two possibilities. If the shape of the earth is known (more precisely,

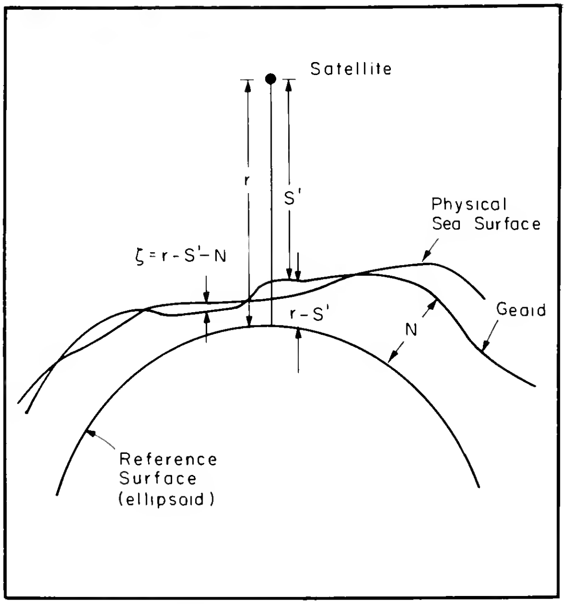
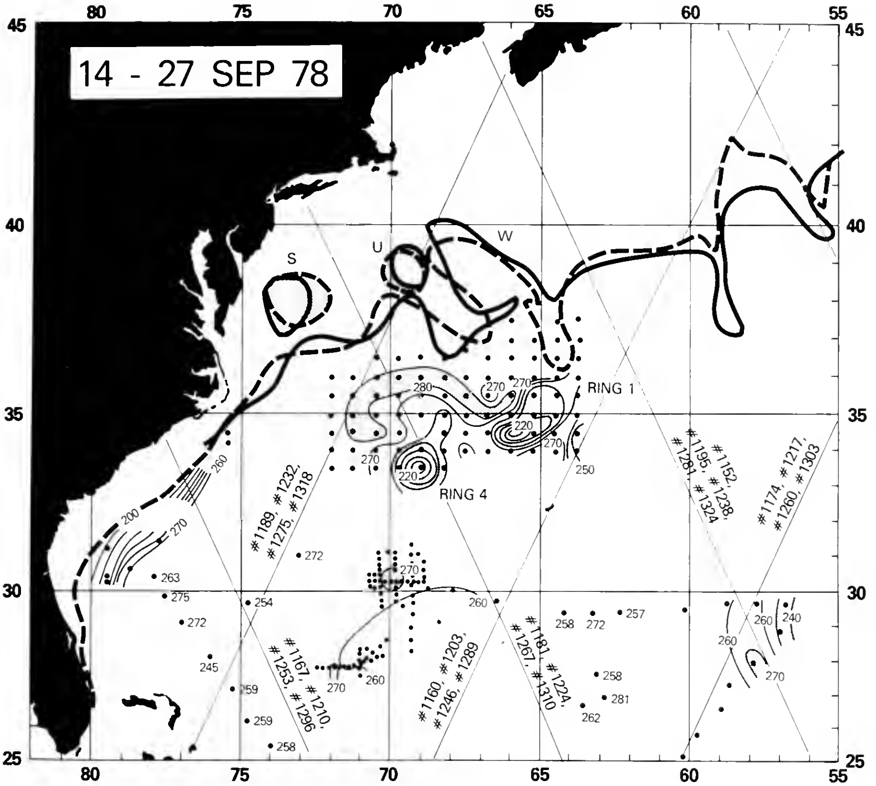


Figure 6. The basic geometry of an altimetric measurement of the ocean by satellite. In practice, the deviation of the sea surface from the geoid is 1 to 2 meters, while the geoid itself goes up and down relative to the reference ellipsoid by 100 to 200 meters. The satellite is tracked, usually by ground-based lasers, to a very high accuracy.



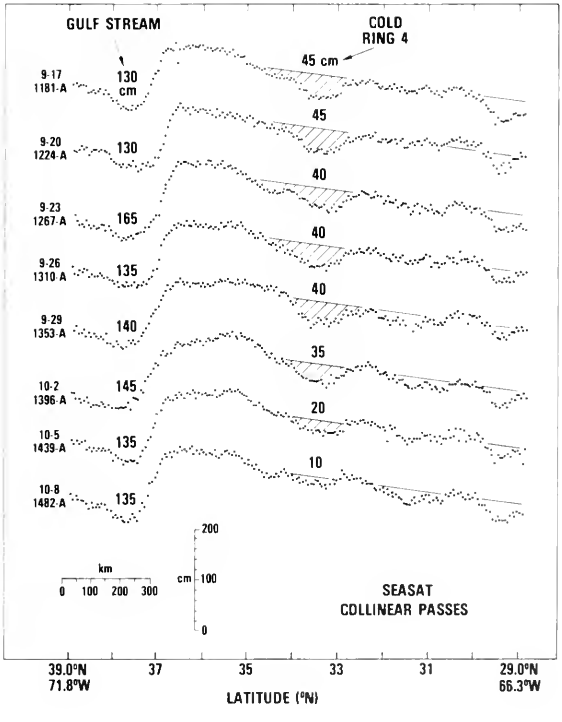
(a)

Figure 7 (a). Seasat ground tracks in the vicinity of the Gulf Stream. (From Cheney and Marsh, 1981) (b) Successive altimetric measurements along set of tracks shown in (a) passing through ring 4, showing evolution of more than 21 days of the Gulf Stream and a large, strong ring. (From Cheney and Marsh, 1981)

the shape that the sea surface would take if no forces acted on the ocean — the geoid) the differences between the actual sea surface and this geoid would show the geostrophic velocity at the sea surface, and therefore remove the need for assuming a level-of-no-motion at depth. Suppose, on the other hand, the geoid were not known (which, in fact, is often the case), but that the satellite passes over the same ground track every few days. Because the geoid does not change, any differences between the sea surface as measured between successive satellite passes must represent changes in the geostrophic water velocities (apart from errors of measurement).

In order to do either of these things, the altimeter and tracking systems must measure to an accuracy of about 5 centimeters or better over distances approaching 1,000 kilometers. Remarkably, NASA engineers and their contractors have been able to do it.

Figure 7 was computed by R. E. Cheney and J. G. Marsh of NASA's Goddard Space Flight Center, from the altimeter on Seasat along the path shown. Seasat was in an orbit that repeated itself almost exactly every three days. In the figure, we see the Gulf Stream and what is called a "ring" to the south. During the time span of the measurement, the ring moves slowly out from under the satellite path, and



(b)

the Gulf Stream moves and changes somewhat as it should. A little mathematics and the use of an estimate of the geoid in this region allow us to compute the absolute surface geostrophic velocities (Figure 8; a different track from those shown in Figure 7 was used).

Seasat failed after three months because of an unfortunate design flaw; it operated long enough, however, to show the intrinsic usefulness of these kind of data. It has led to a number of proposals to fly altimetric satellites.

What could a new, sufficiently accurate, altimetric satellite experiment do? It would provide a global view of the surface elevation of the ocean every few days. Because the surface elevation can be related to the velocity at depth fairly easily, a new altimetric mission could give a fast, quantitative measure of the state of the ocean. But its real value is that by combining altimetric measurements with the equations of motion, we could begin to use the altimeter to provide accurate data for numerical models of the global circulation, both to analyze the state of the sea, and potentially, to forecast it. We could even envision oceanographers at sea, doing hydrographic work in the conventional way, someday able to have direct satellite readout of the surface pressure readout in real time. The need for levels-of-no-motion would finally disappear. The implications of such measurements are very great. For the first time, scientists would have a global view of the sea. They could both map the large-scale movement of water and define its variability.

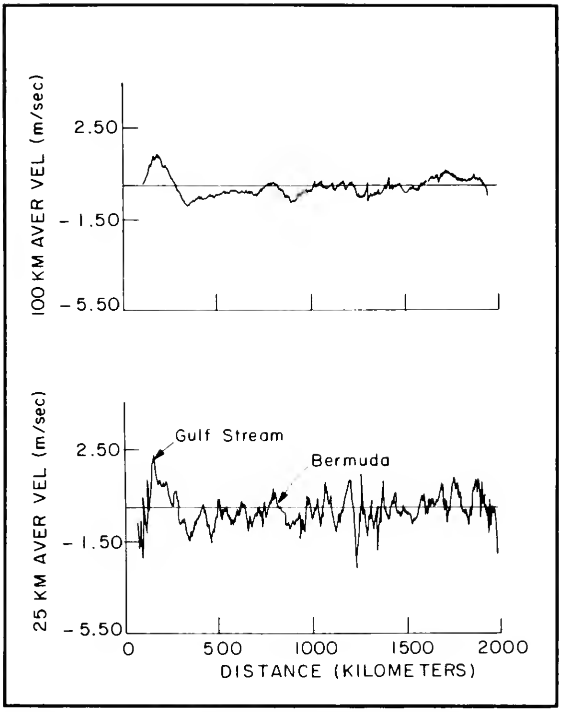
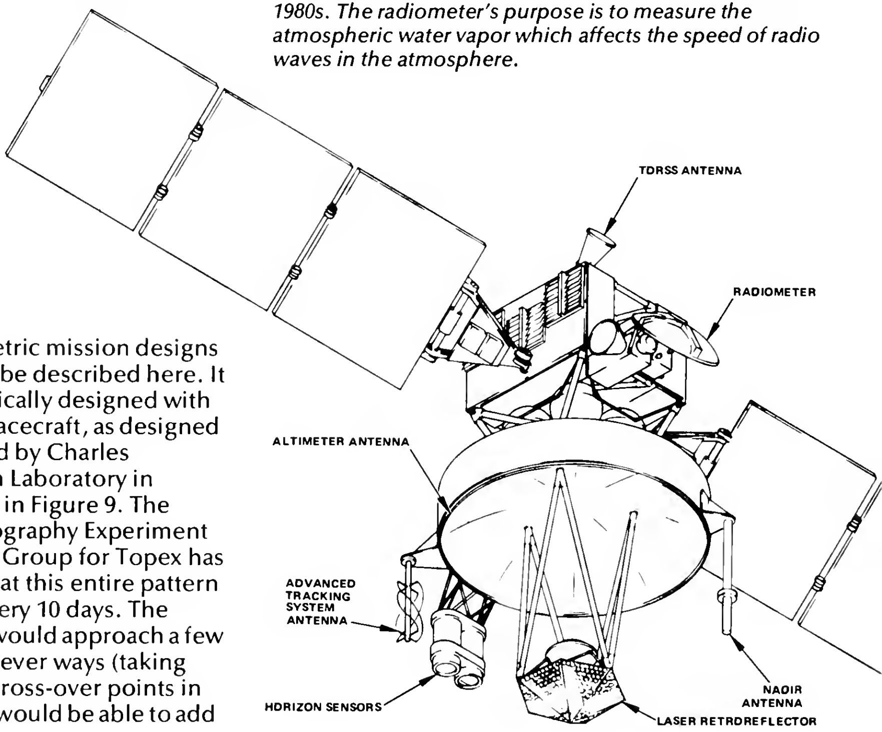


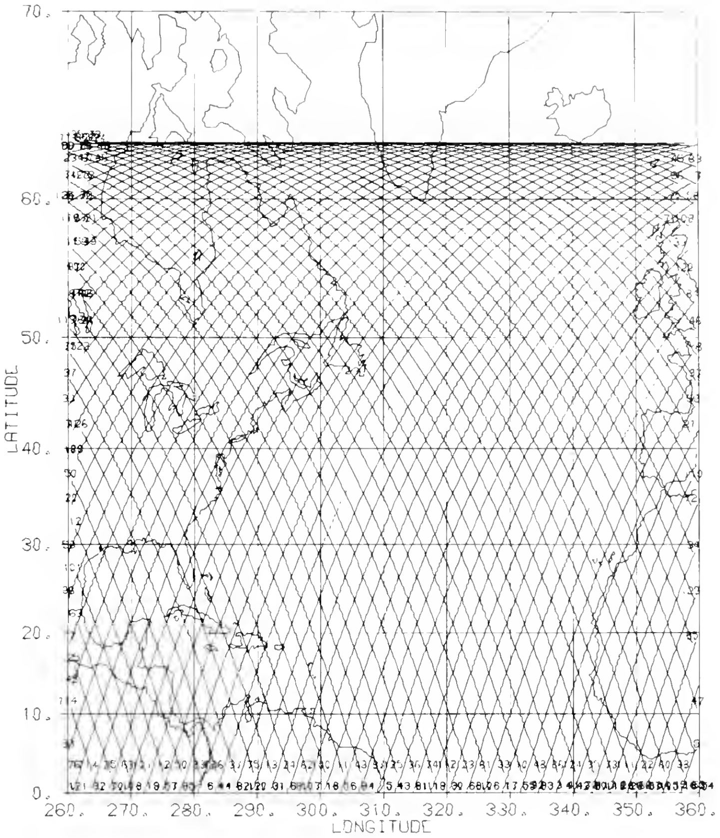
Figure 8. An estimate of the surface velocity in the Gulf Stream and its immediate vicinity from a Seasat altimetric measurement. (From Wunsch and Gaposchkin, 1980)

Figure 9. Engineering design of a proposed altimetric satellite called Topex, which could be flown in mid-to-late 1980s. The radiometer's purpose is to measure the atmospheric water vapor which affects the speed of radio waves in the atmosphere.



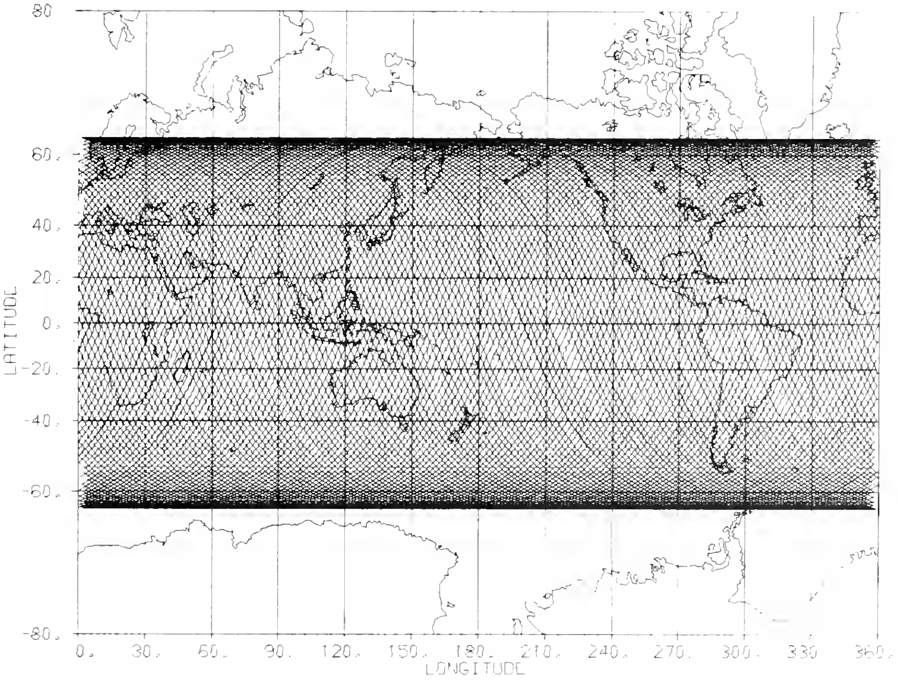
A Mission

There have been several altimetric mission designs since Seasat, but only one will be described here. It is the only such mission specifically designed with scientific goals in mind. The spacecraft, as designed by a team of engineers directed by Charles Yamarone at the Jet Propulsion Laboratory in Pasadena, California, is shown in Figure 9. The proposed name is Ocean Topography Experiment (Topex). The Science Working Group for Topex has proposed that it be flown so that this entire pattern be repeated almost exactly, every 10 days. The accuracy of the measurement would approach a few centimeters. By averaging in clever ways (taking advantage of the fact that the cross-over points in Figure 10 define a surface), we would be able to add



(a)

Figure 10. Ground track coverage for Topex that would be obtained every 10 days for (a) the North Atlantic and (b) the world ocean. Such coverage would determine the surface elevation of the sea globally to a very high accuracy through surface fitting.



(b)

enormously to our information on the behavior of the sea, in terms of both its average state and its variations. For the first time, we would have a global view, a view closely akin and equally valuable to that of the meteorologist.

The Topex mission would have a host of ancillary benefits. The same altimeter measures sea state, wind speed, rainfall, and electron content of the ionosphere. Out of the mission would emerge a much improved determination of the gravity field of the earth. One could study the interaction of waves and currents, mesoscale eddies, or pressing coastal problems. Finally, it would function as an accurate global tide gauge system, eliminating many problems that exist now in tidal measurements.

Such a system could revolutionize our knowledge of the ocean by giving us the requisite vantage point from which to view it. But, contrary to some wishful thinking, satellite systems will not reduce the need for ships and in-situ measurements. If anything, the need for, and the utility of, these more conventional systems will grow. An altimetric mission can only measure the sea surface; we can make inferences about the water movement at depth only from our models (analytical and numerical) and by confirming the validity of these models through in-situ observations. The combination of altimetry with the conventional tools of the oceanographer would be very powerful. Whether the current political and economic state of the world will permit the deployment of such systems remains to be seen.

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Fishing vessel in rough weather on Georges Bank. (Photo by Nubar Alexanian)

The Future for Satellite-Derived Surface Winds

by James J. O'Brien

The wind on the sea affects every facet of the ocean's motion; in fact, it affects all of man's activities related to the sea. The wind creates waves, drives ocean currents, and creates cold upwelled waters (see *Oceanus*, Vol. 21, No. 4, p. 40). It produces downward-cascading bottom water, mixes the heat of the sun from the surface layers to deeper regions, and moves icebergs to their demise in warmer water.

The wind, though, is not responsible for all ocean movement. The sun pumps more energy into tropical regions than into high-latitude areas. This excess heat creates circulation patterns that redistribute the heat poleward. This may occur because of changing atmospheric wind patterns, which cause the wind to create the ocean circulation needed to redistribute the excess tropical heat. Also, the giant killer waves called tsunamis are produced by earthquakes in the ocean floor, not by the wind. These sudden bottom disturbances create very long and energetic waves

The ocean wind vectors of a hurricane. Data from the scatterometer wind measurement instrument aboard NASA's Seasat satellite determined, for the first time, the ocean wind vectors of a hurricane. The wind vectors (white arrows) sensed by the scatterometer are shown as an overlay on a NOAA satellite photograph of Hurricane Fico, taken just before Seasat flew over the hurricane on July 20, 1978. Seasat's subtrack is the black dotted line on the photo. (Photo courtesy of NASA)

(commonly called tidal waves) that are extremely dangerous when they reach land.

Man has always tried to measure the wind over the sea in order to anticipate its effect on oceanic activities. We rely on measurements from continental and island stations as well as from ships. All of us planning to go to sea inquire routinely of the wind and wave forecast. We weigh the weather forecast against our desire to leave the shore. When at sea, we remain aware of the sky and the sea so that we can have an early warning of changing weather.

In sailing days, a good captain could read the sea and the sky and forecast the shift in the currents and the wind-induced waves. In tropical seas, he could forecast the presence of a hurricane hundreds of kilometers away by the strength and direction of the swells. (Swells are what remain of waves after the waves leave the region where wind was created.) But man has never been capable of measuring the wind over an entire ocean on a regular basis. The number of ships at sea, islands, and shore-based stations have always been inadequate for the task. Meteorologists forecast the winds on the sea, but not accurately because of poor data.

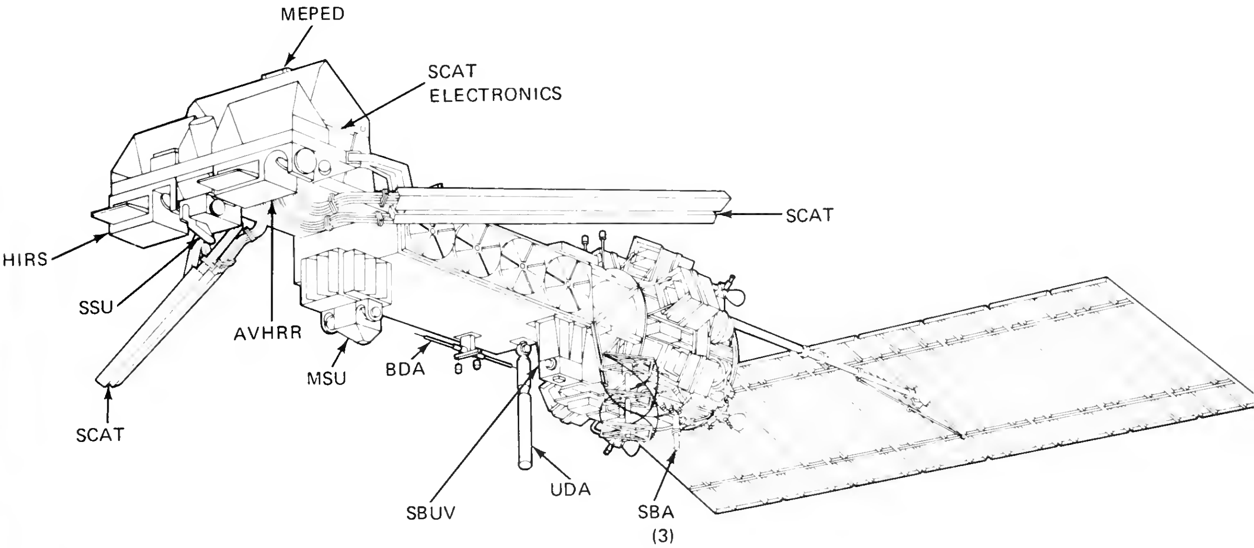
Measuring Winds from a Satellite

It appears technically feasible to measure surface winds from a satellite. In the summer of 1978, the National Aeronautics and Space Administration (NASA) launched Seasat, which was equipped with several experimental instruments. Almost 100 days later, after 1,502 orbits, there was a power failure. On board was a scatterometer, a radar instrument capable of deducing estimates of the wind speed and direction in an ocean patch about 50 kilometers on each side. We are not quite sure exactly how the instrument works, but we do know it sends a radar beam to the ocean and measures the amount of back-scattered radar energy. It is supposed to measure the intensity of the wavelets in the ocean patch. Wavelets are very small 5- to 10-centimeter waves that ride on the back of bigger waves. The premise is that the intensity, strength, and quantity of these little waves are related to the wind speed at the same place and time. Some of the data from Seasat have been carefully examined by oceanographers and meteorologists and there is cautious agreement that the scatterometer is capable of measuring wind speed in many weather situations to within 2 meters per second (approximately 5 miles per hour). The wind scatterometer is also capable of measuring wind direction except it always has a 180-degree bias — for example, it cannot tell north from south or east from west. Most meteorologists can remove this bias by looking at a standard satellite view of the earth and noting the position of storm centers.

Why Use Satellites?

A wind scatterometer mounted on an orbiting spacecraft would estimate the surface wind speed and direction below its path as it moved around the earth. If the orbit were adjusted to altitudes of about 2,400 kilometers, the satellite could cover the entire globe in a few days. For the first time in our history, we would have global distribution of wind estimates every week or so. These would be used in a variety of ocean models to simulate ocean surface currents on many space and time scales. In essence, we would be able to estimate the distribution of ocean currents over an entire ocean and their changes on a day-by-day basis. The wind field derived from the radar reflection from the tiny wavelets would in turn be used to derive pictures of the ocean movement. This cannot be done from buoys and ships, since an enormous number of platforms would be required, but appears to be possible from satellites. Thus we would be measuring the wind at the surface of the ocean from an instrument located 2,400 kilometers in the sky.

All of us remember the excitement we felt when our first astronauts flew into space and brought back those remarkable pictures of the earth. We anticipate that the ocean-current charts determined by the wind scatterometer will be as



NOAA-H, one of the current series of polar-orbiting operational meteorological spacecraft. A study, examining the feasibility of placing a scatterometer (SCAT) on this spacecraft, in addition to the standard complement of sensors, is under way. The earliest launch date for this particular spacecraft is 1985; a typical spacecraft of this series has a length of 4.2 meters, weight of 935 kilograms, and average power consumption of 550 watts. HIRS — High Resolution Infrared Sounder (lower atmospheric temperature profiles); SSU — Stratospheric Sounding Unit (upper atmospheric temperature profiles); AVHRR — Advanced Very High Resolution Radiometer (cloud and sea-surface temperature images); MSU — Microwave Sounding Unit (correction of HIRS profiles in presence of clouds); BDA — Beacon Command Antenna (for low data rate transmissions and command/control); SBUV — Solar Backscatter Ultraviolet Spectrometer (atmospheric ozone profiles and images); UDA — UHF Data Collection System Antenna (locates remote platforms and relays their data to ground); SBA — S-Band Antenna (for high data rate transmissions); and MEPED — Medium Energy Proton and Electron Detector (monitors solar emission for communications). (Sketch courtesy of RCA) informative and instructive as those first cloud pictures. We will be able to calculate the major current patterns and their variability on a week-by-week basis; and locate new and intriguing swirls, bands, rolls, and vortices that we only suspected to exist before. Though this is all speculation, we have hints of such variability from recent expeditions and theoretical calculations.

Wind-Driven Currents

In 1896, the Norwegian F. Nansen returned from being locked in the Arctic ice over the winter. On his way home, he observed that icebergs did not drift in the direction of the wind but to the right of the wind. A young Swede named Ekman solved the puzzle. The relatively slow motion of the wind on the ice is influenced by the rotation of the earth. When the wind sets the water in motion, the transport of the upper layers is to the right of the wind in the Northern Hemisphere. This is the Ekman drift current. Thus in the open ocean, we expect to find the flow of the upper ocean (a few tens of meters) moving to the right of the wind (to the left in the southern oceans). With a satellite wind-observing system, the Ekman drift current could be calculated on a regular basis. These estimates would be useful for search and rescue operations, as well as for pollution transport problems. Oil spills, for example, are believed to be influenced by this drift current.

Using quality wind fields, we could make many new and interesting calculations. It has been observed that the strength and position of strong currents, such as the Gulf Stream, vary throughout the year. The Gulf Stream meanders and creates rings and eddies. There are numerical models of the Atlantic Ocean that could use the satellite-derived winds to estimate the ocean currents at different seasons (see *Oceanus*, Vol. 19, No. 3). These calculations would no doubt yield information about the physical mechanisms of the variability being observed.

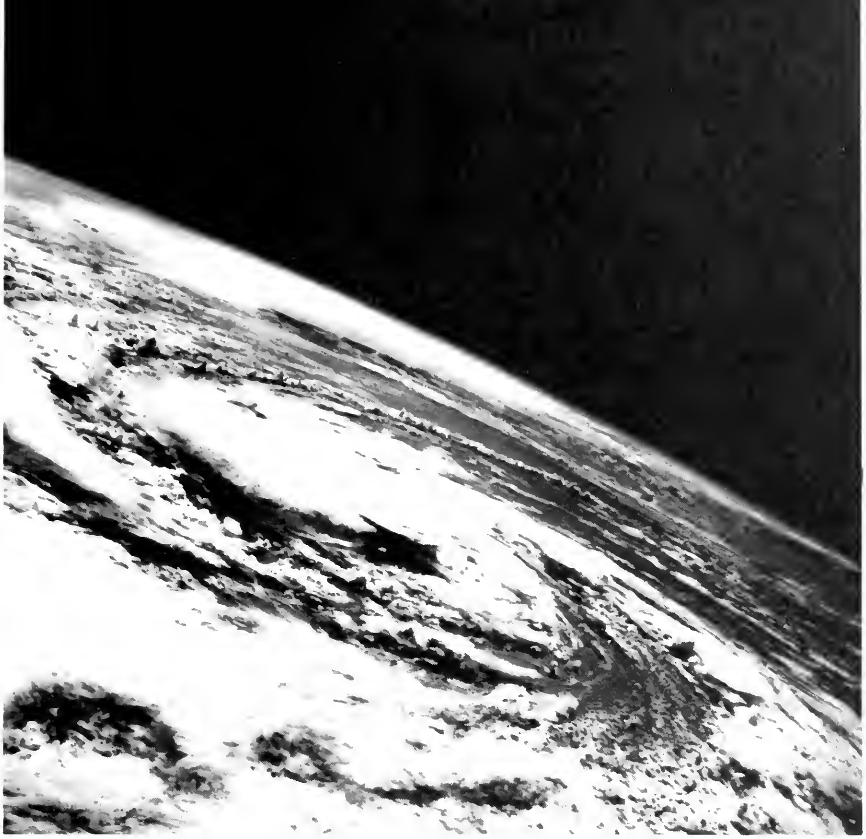
The El Niño Phenomenon

In 1978, *Oceanus* published (Vol. 21, No. 4) an article on El Niño, a large climatic fluctuation in the eastern equatorial Pacific. Every few years, a large pool of anomalous warm water appears off Ecuador and Peru around Christmastime. During the year, it spreads westward across the equator and induces massive rains to fall on tropical islands that are not used to rain. As the young anchoveta larvae cannot tolerate the abnormal ocean climate, the fisheries of Ecuador and Peru lose an entire year class. The recent El Niños occurred in 1976-1977, 1972-1973, 1968-1969, 1965, and 1957-1958. Another interesting correlation with El Niño is that these years happen to have had the most severe winters in the eastern half of the United States. If we were able to forecast the occurrence of El Niño, we might be able to predict the likelihood of a severe winter in the northeastern states. At present, we do not understand how large, warm temperature patches of ocean affect the weather thousands of kilometers away. However, we have some knowledge of the oceanic behavior that leads to an El Niño.

In the tropical regions, the ocean is capped with a warm surface layer a few hundred meters thick called the upper-ocean mixed layer. The region separating the upper warm layer from the bottom is called the thermocline (the ocean layer through which temperature changes rapidly with depth). In the Pacific, the equatorial winds generally blow toward the west, which stacks the warm water up on the west side. The warm water is about 300 meters deep off New Guinea and 100 meters deep off Ecuador. Associated with this east-west tilt of the thermocline (the boundary between the warm surface water and the colder deeper ocean) is a strong west-to-east setting current called the equatorial undercurrent. Thus, on average, the winds drive the surface waters to the west and the undercurrent returns the water to the east. The winds toward the west also induce equatorial upwelling of the deeper water which produces a relatively cold strip of ocean along the equator.

El Niño occurs when the winds cease to blow toward the west. We now believe that the region of weaker winds blowing toward the west is located west of the Dateline in October and November of the year preceding an El Niño. The abnormal winds are from the west and create a patch of deep warm water several thousand kilometers long. This warm water then moves at speeds of 200 to 300 kilometers per day toward Ecuador as a phenomenon known as an internal Kelvin wave. When the warm water reaches the coast of South America, it deepens the mixed layer along the coast of Ecuador and Peru and north to Baja, California. This deep surface layer isolates the cold water below. Thus the usual upwelling of cold water is reduced. The turbulent entrainment of the cooler subsurface water is reduced. Consequently, the sun warms up the surface layer, and creates the pool of warm water. This complicated process has only recently been understood. If we could forecast the creation of the warm pool off South America, we might be able to predict very cold winters in the eastern United States — and damages to the fisheries off northwestern South America.

If our present ideas are correct, we should be able to make some prediction of an El Niño by measuring the winds over the western Pacific along the equator. The appearance of strong westerly winds in the trigger region would allow us to forecast an impending El Niño. If Topex (see page 17) was in space we would be able to monitor the passage of the Kelvin wave as it moves eastward toward Ecuador. Using infrared sea-surface



Hurricane Gladys, packing winds of 80 knots, swirls about 150 miles southwest of Tampa, Florida, in October of 1968. Photograph was taken from the Apollo 7 spacecraft at an altitude of 97 nautical miles. (Photo courtesy of NASA)

temperature measurements, we would be able to measure from space the development of the warm anomaly along the coast. With this sequence of space-technology products, we might be able to forecast an El Niño occurrence a few months in advance.

The Indian Monsoon

The main advantage of the wind scatterometer will be that, instead of receiving wind records from islands or buoys which record continuously in time at a single point, we can get measurements of the wind occurring along the satellite track. As the satellite circles the globe, its instruments gather wind data from the sea surface. As the orbits cover the globe, a map of wind vectors can be constructed, allowing us to investigate the large-scale wind systems — such as the trade-wind regimes — over the oceans. In particular, we will be able to calculate the effect of the Indian monsoon on the circulation of the Arabian Sea.

The Indian monsoon is one of the most important wind patterns in the world. During the summer months (June to October) the winds over the Arabian Sea blow from the southwest toward India and bring moisture for agriculture. During the winter (November to March), the winds reverse and blow from the northeast. The timing of the onset of the southwest monsoon is critical for the food supply of India. If the rains come too soon, the fields are muddy; if late, the seedlings die.

Meteorologists and oceanographers believe that the Indian Ocean heat content may be a factor in the behavior of the monsoon. The distribution of heat in the Indian Ocean is determined by air-sea interactions and the general ocean circulation. The ability to measure the winds over the Indian Ocean and to calculate the ocean circulation will greatly enhance our understanding of the monsoon.

The Future

Although the United States has led the world in space exploration, other nations are investing in this technology. The European Space Agency, the Japanese, and the Soviet Union have the capability to launch a satellite with a wind scatterometer. It takes several years of planning and engineering studies to prepare for a specific space venture. We can expect that by the late 1980s, there will be one or more wind scatterometers orbiting the globe. If we learn how to interpret the data from the radar backscatter as wind speed and direction at the sea surface, we will be able to make estimates of waves and currents. These data will accelerate our understanding of the ocean.

James J. O'Brien is Professor of Meteorology and Oceanography at The Florida State University, Tallahassee, Florida.

Suggested Readings

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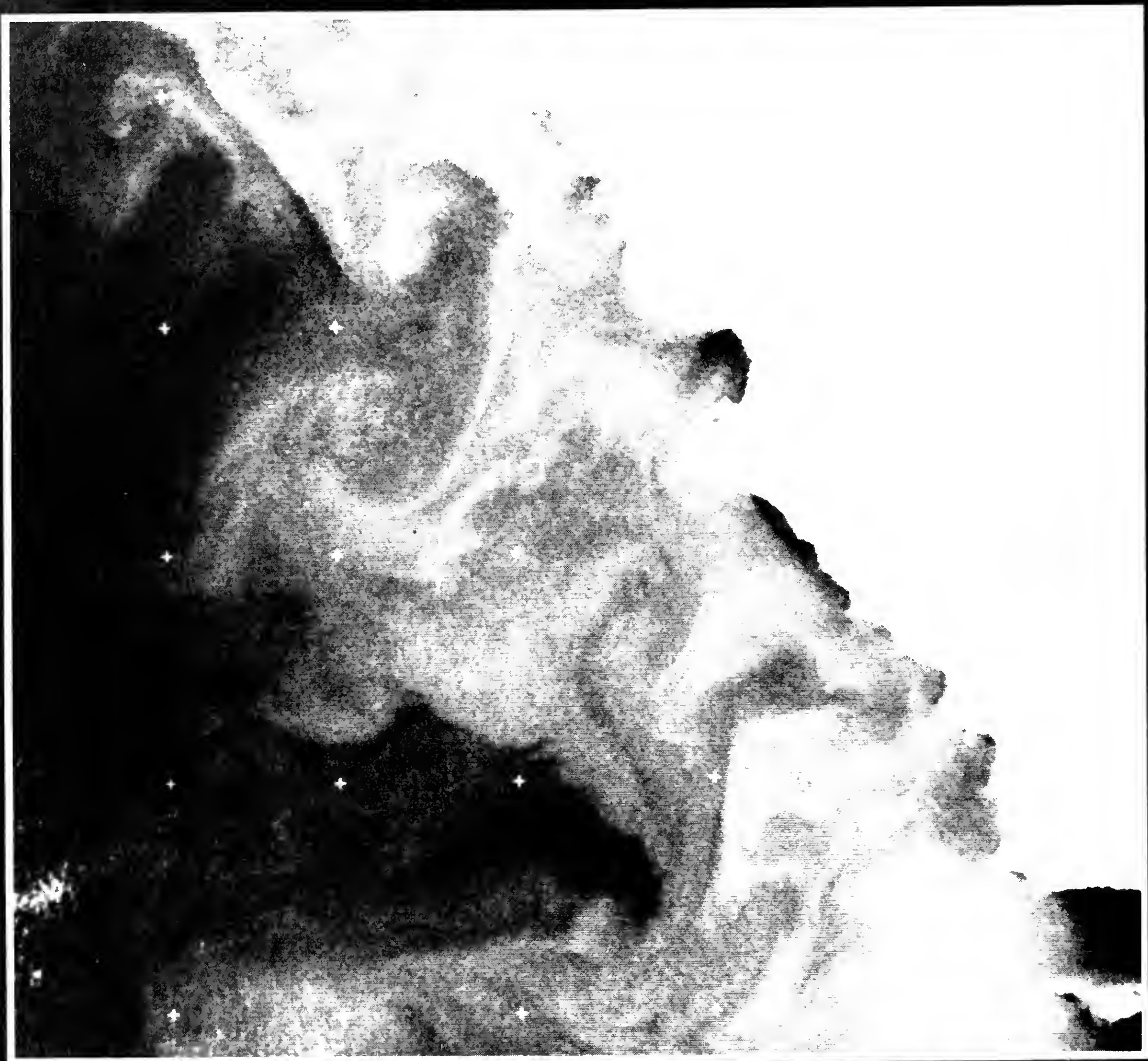
Remote Sensing in Biological Oceanography

by Wayne E. Esaias



Relative concentrations of chlorophyll-like pigments are shown along the California coastline (at right) as transmitted by the Coastal Zone Color Scanner aboard Nimbus-7 on July 7, 1981. Upwelling, eddies, and other thermal ocean structures can also be seen. The image was processed at the Scripps Institution of Oceanography's Remote Sensing Facility.

The fundamental goal for virtually all ecological research is to understand and explain the abundance and distribution of organisms in space and time. Although this goal may never be fully achieved, it nevertheless is what we must strive for. The goal implies first that we can determine levels of abundance and distribution of organisms at a given place and at a given time, and, second, that we know enough about the ecological, physiological, biological, and physical processes that control these factors to predict how such populations will change with time and with changes in the environment.

There is a general appreciation by ecologists, politicians, and the informed public that we are facing many critical problems concerning the earth's closed ecosystem and our interaction within it. This has led to increased efforts to further our understanding of the link between man and his environment and between the various components of the ecosystem. Some of these concerns are fairly specific; for instance, how to prevent the extinction of certain valued species. Others are more complex, such as how to more effectively manage or increase the yield from marine resources. Still others are even more complicated, such as how activities affect global cycling of material within our closed ecosystem. A timely example is to determine the relationship between fossil-fuel production of carbon dioxide, global primary production, global climate (the greenhouse effect), and increased production of plant nutrients for agricultural purposes (which leads to increased levels of nutrients in rivers and estuaries) — all critical to our understanding of the global carbon cycle. These types of problems require the best possible approximations since misunderstandings and false assumptions about how the ecosystem operates can only decrease our ability to arrive at correct decisions and solutions.

Spatial and Temporal Scales

The oceans cover nearly three-fourths of the earth and are extremely important in the overall ecology and cycling of matter and energy. Within the oceans, biological and physical processes take place and interact over wide ranges of space and time. A portion of the universe is depicted in Figure 1 and illustrates the general role that remote sensing must play in our attempts to achieve the objectives stated previously.

Organisms are not distributed uniformly, nor do they interact everywhere simultaneously. Through the efforts of scientists such as John Steele, Director of the Woods Hole Oceanographic Institution, and Trevor Platt of the Bedford Institute of Oceanography, and their colleagues, we have learned a great deal about the nonuniformity of organism distributions and its causes and ramifications — known as the "patchiness problem." Organism activities exhibit variations over a range of space and time, determining the scales that must be studied in the oceans. For example, major changes in the phytoplankton community occur over weeks or less, during which time individuals may experience similar conditions over areas of about 10 to 100 square kilometers. Fish — because they are larger, swim faster, and are longer lived — experience the universe on the order of years and over regions of up to millions of square kilometers.

Assessment Studies

To document the changes in the abundance and distribution of phytoplankton, we need to assess, synoptically, areas upward of 1 square kilometer and to repeat this at intervals of several days. A ship, proceeding at a nominal 10 knots (5 meters per second), is a poor platform from which to make this assessment. It moves too slowly to permit separation of time-dependent changes within populations from spatial (either geographical or current- induced) changes in distribution, even though shipboard investigators can perceive that both types are invariably occurring. The aphorism about stepping in the same river twice might be amended, without excessive hyperbole, to say that the oceanographer cannot step in the same ocean twice. The ship domain, limited by its speed and ability to cover an area, lies to the right of the diagonal line in Figure 1. Bear in mind that if the assessment takes time on stations, the domain is reduced considerably.

Comparing the domains for various processes and distributions with the domains for the various sampling platforms, we arrive at a major reason for the development of remote-sensing techniques — the need to measure distributions of properties over larger areas synoptically. Synopticity, having an overall view of how things are at that point in time, is essential for documenting abundance and distribution and elucidating mechanisms of change in both the physical and biological realms. Extending synoptic measurements beyond the ship domain could serve as one definition of remote sensing. Measurements taken from instruments on a buoy can usually be made by a ship, but a ship, or even a fleet; cannot duplicate areal coverage by aircraft and satellites. In many respects, these platforms collect mutually exclusive but complementary data sets, all of which are required if we are to properly assess problems of abundance and distribution.

For example, to measure chlorophyll over the New England shelf by shipboard techniques we would need up to 30 days to reproduce the large-scale spatial structure shown in Figure 2. During this time, the populations would have changed considerably. Perhaps as many as four

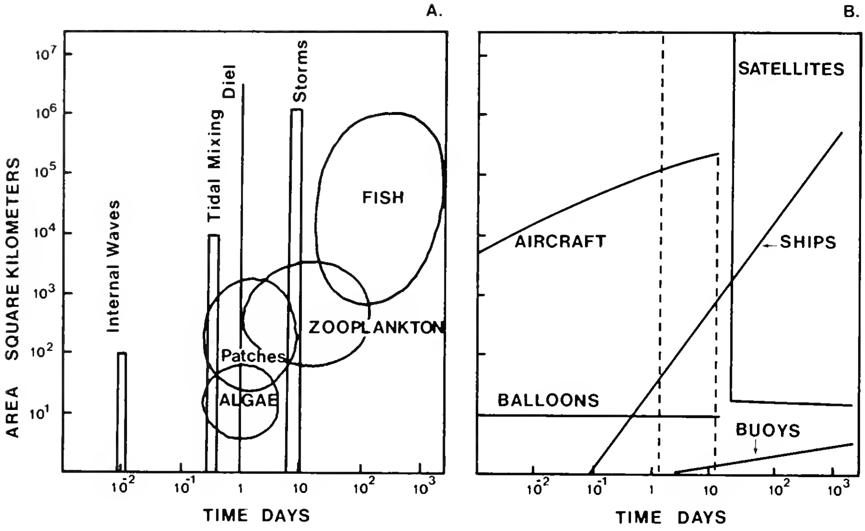


Figure 1. Simplified space and time domains for some oceanic processes and sampling. A. Processes, indicating periods for physical forcings and excursion-generation times for biological components. B. Sampling, indicating limits of coverage for various research platforms. Domains above and to the left of delineated areas are undersampled by the platform.

storms would have passed through the area, further confusing interpretation of the observed distributions.

There also are some major constraints involving remote-sensing techniques, the two most important of which are that presently only near-surface properties are measurable and, second, that only a limited set of all properties of interest are sensible at all. Adding the third dimension, depth, would be of considerable value as would additional property measurement techniques.

However, much can be done with surface distributions of key physical and biological properties as long as they are measured simultaneously so that we can address process interactions. If the vertical processes that produce observed surface distributions can be determined, inferences (based on surface measurements) can be made regarding the subsurface properties.

Process-Oriented Studies

A phrase often used by ecosystem modelers, "physical forcing functions," denotes those physical events or processes — such as wind mixing, currents, and light attenuation — that are critical for phytoplankton growth. Understanding the physical events is a prerequisite for understanding the biological processes. These processes, such as growth, feeding, nutrient uptake, predation (grazing), and reproduction, are

Figure 2. Chlorophyll distribution over the Nantucket Shoals-Georges Bank region. Lighter shades indicate higher chlorophyll values. This image was produced by R. C. Smith of the Scripps Visibility Laboratory using data taken by the Coastal Zone Color Scanner on Nimbus-7.

closely linked to one another, but also are closely related to the physics of the situation — such as water movement. It is improper for a zooplankton-grazing specialist, for example, to work with no input concerning the phytoplankton assemblage activity, current structure, speed, and direction, or predation, of zooplankton. The study of these biological rates involves a great deal of interactive work, in which many other biological processes also must be understood, or at least measured nearly concurrently.

The trend over the last few decades in biological oceanography was toward large, inter-disciplinary activities in which several large vessels were equipped to cover nearly all bases and were devoted to a given problem or process for periods of weeks to months over several years. For these investigations, smaller-scale and repeated synoptic measurements of abundance and distribution may allow expensive sea-going research centers to place themselves at the right spot to properly study the mechanics of how and why things change.

The requirements of this type of remote sensing are slightly different from the "simple" assessment of abundance and distribution discussed previously in that smaller areas of the ocean are involved. There is a need for fast data processing and transfer, with interaction between the remote-sensing and shipboard program. Because of fixed experiment scheduling, optimal remote-sensing conditions are often precluded. This "produce on demand" requirement severely limits some types of technology, such as visible satellite coverage in overcast regions, and it requires that the remote-sensing program be operational instead of research-oriented.

In most cases, remote sensors do not directly measure those things which are of prime concern in biological oceanography in the sense that sea-surface temperature is of prime concern to some meteorologists, or that salinity is of prime concern to those doing salt-balance calculations. We will never be able to directly measure from space how organisms interact with their environment, only some results of that interaction. This sometimes poses difficulties in justification. Remote-sensing techniques can provide an assessment of the present state of the system's surface, which is absolutely necessary as a framework for the measurements and processes under investigation.

Most of the biological activity in the oceans occurs over a relatively small fraction of its area and these "hot spots" are predominantly coastal. In these regions, the physical regime is characterized by relatively high horizontal and temporal gradients. The assessment of these gradients does not require the high precision necessary for most open-ocean physical dynamics studies. For example, investigations of the impacts of estuarine outflows on continental shelf ecosystems are well served by the microwave radiometers operating at L-band frequencies, which can measure salinity with 0.5 parts per thousand accuracy and 50-square-meter spatial resolution.

The major application of remote sensing to biological oceanography is measuring concentrations of cellular plant pigments as an estimate of phytoplankton abundance and levels of primary production. Phytoplankton photosynthetic pigments are the single most important contributor to ocean color. Chlorophyll *a* is the primary photosynthetic pigment found in all plants and is also highly fluorescent. Both ocean color and chlorophyll fluorescence are accurately measured by remote techniques with sufficient precision to give excellent estimates of chlorophyll concentrations and hence phytoplankton abundance.

Along with suspended sediments and gelbstoff (yellow material derived from degraded terrestrial and marine plant remains), phytoplankton and their pigment concentration control light penetration and hence the depth throughout which useful photosynthesis can occur (euphotic zone). The coefficient of light attenuation also can be determined remotely by measurements of ocean color and by laser light-scattering techniques, perhaps even more accurately than we can measure phytoplankton. This measurement is used to specify the depth of the euphotic zone.

Knowing the euphotic zone depth, the incident light intensity, and phytoplankton concentrations, we can estimate the rate of photosynthesis, or primary production of particulate matter in the sea. These rates serve as a major input to research on marine ecology, food chains, and fisheries management. The distributions of phytoplankton and primary production also help fisheries determine resource location, since most fishing occurs in highly productive regions.

Role in Ecosystem Models

As is the case for meteorological forecasting, the predictive capability of mathematical simulations of oceanic ecosystems is limited by inaccuracies in our knowledge of the initial state or conditions of the system as well as in our knowledge of how and at what rate the components interact. The basic physics problem of the trajectory of a ball in flight offers an appropriate analogy. To predict where the ball will be at a particular time, we must know a specific position and velocity as well as the laws of physics acting on it. The ocean is very poorly sampled, especially with respect to biology, and large-scale synoptic assessments of distribution available through remote-sensing techniques are critical if the initial conditions are to be specified. Such models must be updated frequently; we must respecify the state of the system as it changes. This is especially true for ecosystems, since our knowledge of the principles of interaction and estimates of rates of interaction are much poorer than for meteorology.

Coastal Zone Color Scanner

The image shown in Figure 2 was produced by Raymond Smith of the Scripps Institution of Oceanography from data obtained on June 10, 1979, by the Coastal Zone Color Scanner (CZCS) on board Nimbus-7. It shows the northeast coast of the United States and chlorophyll *a* distributions in the surrounding waters. Here, lighter shades of gray indicate higher phytoplankton concentrations. High chlorophyll concentrations can be seen over Nantucket Shoals and Georges Bank, south and east of Cape Cod. These areas are very productive in both phytoplankton and fishes; interest centers on how these ecosystems operate and maintain such high levels of productivity. Farther to the south, large areas obscured by clouds are outlined in white.

The methods (algorithms) used to produce the CZCS image were optimized for the southern California bight region. Although atmospheric and water optical properties are undoubtedly different in the northeast United States, the relative differences are probably reasonable to within a factor of three or so.

The zigzag line east of Nantucket is the track of the *R/V Edgerton*, May 19-23, 1979, which sampled surface chlorophyll and hydrographic properties under a joint Woods Hole Oceanographic Institution/Brookhaven National Laboratory program. Whether the plume-like feature over the ship track is chlorophyll, an atmospheric effect, or water feature is not clear. We would have liked an image coinciding with ship sampling, but clouds and ship schedule constraints prevented this, as is often the case.

The image clearly indicates the mesoscale distribution of chlorophyll as related to the large-scale bathymetric features of the shoals and bank. These data are extremely useful for guiding future investigation of such ecosystems, both conceptually and for providing quantitative assessments of phytoplankton standing stock in these well-mixed regions.

The CZCS instrument on Nimbus-7 will last, at best, for only a few years. A replacement was planned as part of the National Oceanographic Satellite System (NOSS), now eliminated because of budget restrictions. An attractive alternative satellite platform for the CZCS/2 is the National Oceanic and Atmospheric Administration (NOAA) meteorological satellite (Figure 3). This option could fill the gap, beginning in 1985. Space shuttle

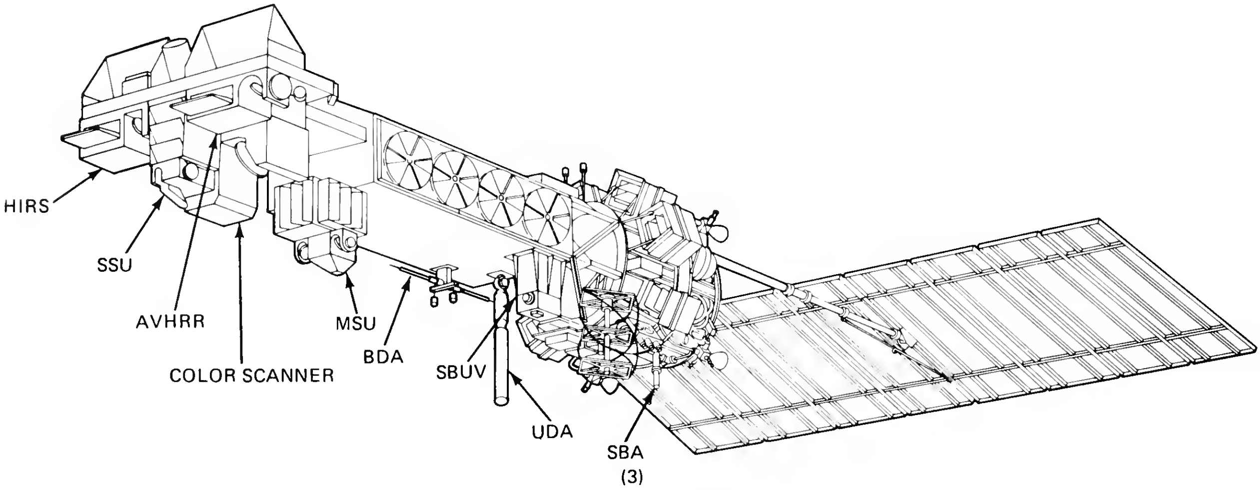
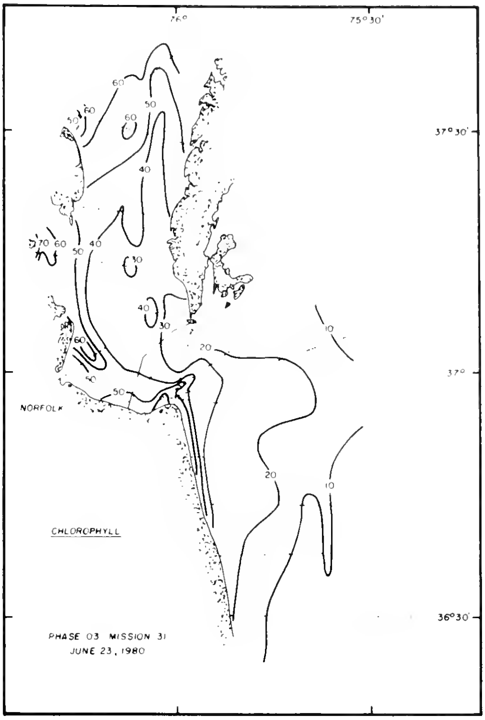


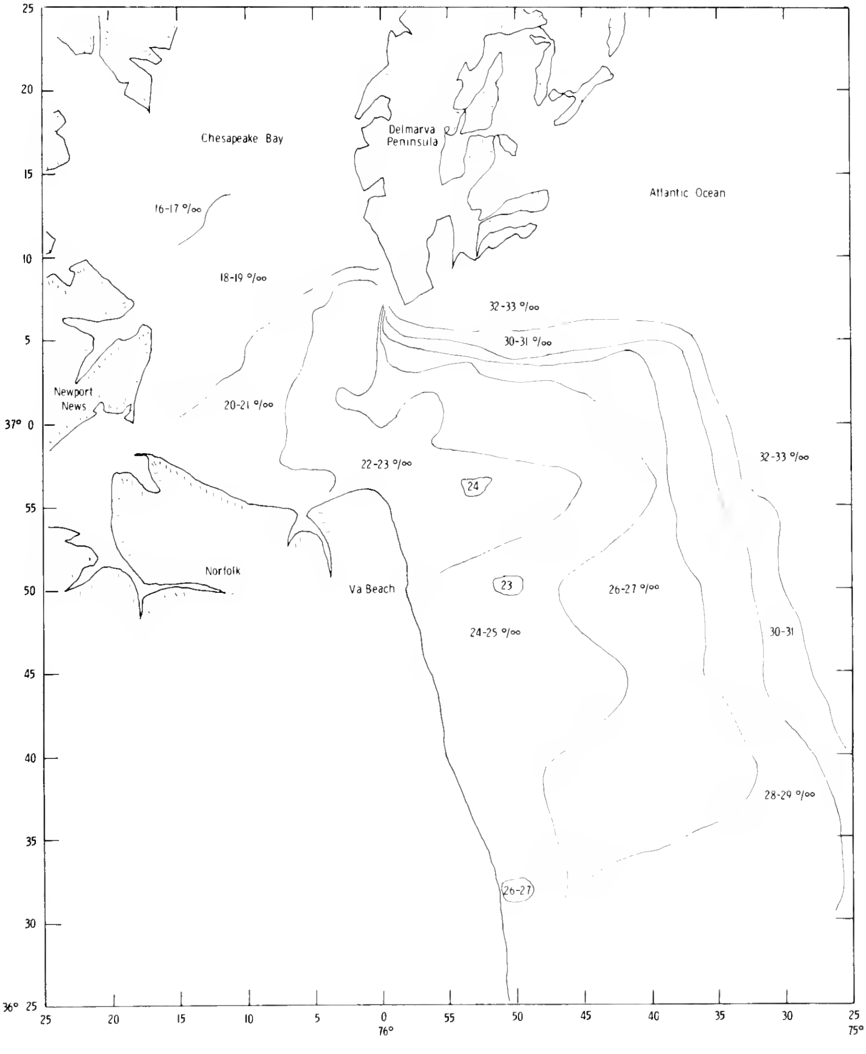
Figure 3. NOAA-H, one of the current series of polar-orbiting operational meteorological spacecraft. A study, examining the feasibility of placing a color scanner on this spacecraft, in addition to the standard complement of sensors, is under way. The earliest launch date for this particular spacecraft is 1985; a typical spacecraft of this series has a length of 4.2 meters, weight of 935 kilograms, and average power consumption of 550 watts. HIRS — High Resolution Infrared Sounder (lower atmospheric temperature profiles); SSU — Stratospheric Sounding Unit (upper atmospheric temperature profiles); AVHRR — Advanced Very High Resolution Radiometer (cloud and sea-surface temperature images); MSU — Microwave Sounding Unit (correction of HIRS profiles in presence of clouds); BDA — Beacon Command Antenna (for low data rate transmissions and command/control); SBUV — Solar Backscatter Ultraviolet Spectrometer (atmospheric ozone profiles and images); UDA — UHF Data Collection System Antenna (locates remote platforms and relays their data to ground); and SBA — S-Band Antenna (for high data rate transmissions). (Sketch courtesy of RCA)

Figure 4. Distribution of chlorophyll fluorescence (a) and salinity (b) in the Chesapeake Bay region, 0600-0833, June 23, 1980. These data were taken by the NASA-Wallops Airborne Oceanographic Lidar (courtesy F. Hoge) and the NASA-Langley L-Band Microwave Radiometer (courtesy B. Kendall) simultaneously from a P-3 aircraft flying at 500 feet. Data were recorded at 6¼ and 3 times per second with 10 to 30 meter resolution along the flight track (dotted lines), and were contoured by hand. Chlorophyll a concentrations ranged from 0.2 to 12 μg l, and were highly correlated with fluorescence (r^2 = 0.93).

(a)



(b)



deployment also is a possibility, but the orbital configuration is far from ideal for a color scanner and would eliminate coverage at high latitudes.

Lidar Techniques

Only the top several meters of the ocean are sampled directly through passive visible optical techniques. For microwave and infrared wavelengths, the remote signal originates in the upper few centimeters or millimeters. Lidar (light detection and ranging) techniques using aircraft or ship-mounted lasers will enable this depth range to be extended much deeper. By sampling the returned signal at very short (10^{-9} second or nanosecond) intervals, we can measure depth profiles rather than depth-averaged values of properties. These properties include chlorophyll *a*, other fluorescent pigments, particle abundance, and temperature. The penetration, or remote-sensing depth, may thus be extended to the entire euphotic zone, or depths over which net positive photosynthesis occurs.

Several aircraft laser instruments have been developed to refine and demonstrate these techniques. The Airborne Oceanographic Lidar (AOL) developed by Frank Hoge and coworkers at the National Aeronautics and Space Administration's (NASA's) Wallops Flight Center has been used extensively to measure light attenuation and the fluorescence of chlorophyll, phycoerythrin, and dissolved organic material at several locations off the east coast. Michael Bristow of the Las Vegas Environmental Protection Agency (EPA) laboratory has also developed a laser fluorosensor that has been used to measure chlorophyll and dissolved organic material fluorescence in Lake Mead, Nevada/Arizona.

Aircraft systems provide excellent Lidar platforms for coverage of short to medium space and time scales. By combining physical sensors (microwave and thermal) with biological sensors (color sensors and Lidars), we can address a large number of highly dynamic ecosystem processes. NASA's Langley Research Center and the Northeast Fisheries Center of the National Marine Fisheries Service (NMFS) have jointly used these systems in a study of the effects of the Chesapeake Bay plume on the coastal ocean. Figure 4 shows distributions of salinity and chlorophyll fluorescence off Chesapeake Bay. The bay waters exit from the southern side of the bay mouth and become entrained in a southern flow, evident through lower salinity values recorded by the microwave radiometer. Chlorophyll levels are highest in the bay, and phytoplankton entrained in this water are distributed very much like the freshwater component of the bay plume. These data were taken near ebb tide over a 3-hour period. Several bulges are noted in the distributions which appear to be related to ebb tides. Other remote-sensing systems also were used in this study. Investigators from more than 15 other institutions and agencies were on board vessels to measure key biological, chemical, and physical processes, including trace metals, hydrocarbons, and bacterial distributions. The synoptic aircraft distributions enabled the nonsynoptic ship measurements to be placed in the proper physical perspective.

In summary, remote-sensing techniques play an extremely valuable role in biological oceanography. Their major attribute lies in the ability to measure distributions over large areas on a synoptic basis and to repeat this coverage at required time periods. This coverage cannot be made from ship platforms and is necessary in order to extend ship and buoy measurements to aid in assessment and in the investigation of spatial and temporal variations in interactions between organisms and the environment.

Wayne E. Esaias received his Ph.D. in biological oceanography from Oregon State University in 1972. His subsequent work on underwater optics and how physical processes affect spatial distributions of phytoplankton led to his joining the remote-sensing investigations in 1979 at NASA's Langley Research Center in Hampton, Virginia.

Recommended Reading

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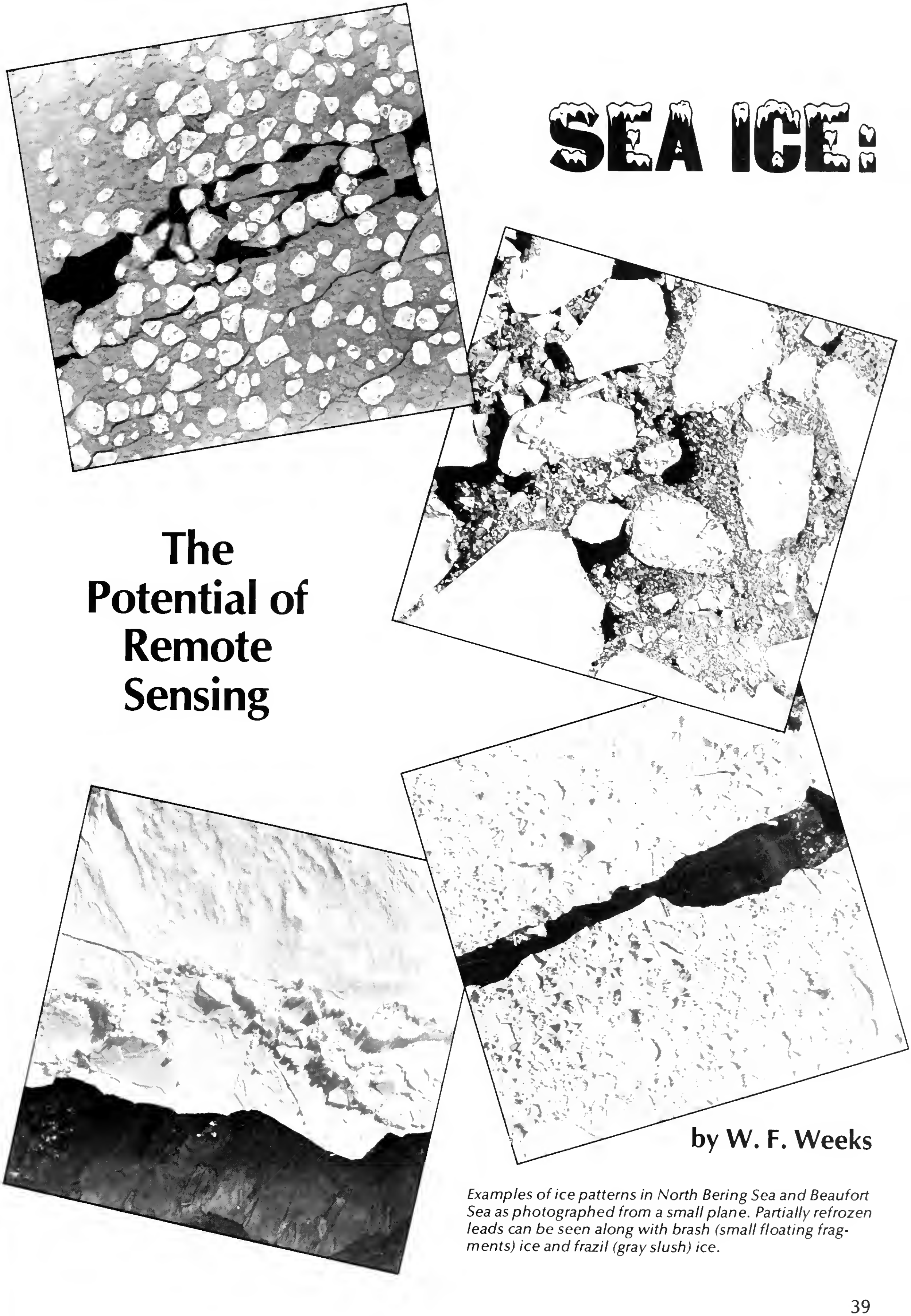
SEA ICE:

The Potential of Remote Sensing



by W. F. Weeks

Examples of ice patterns in North Bering Sea and Beaufort Sea as photographed from a small plane. Partially refrozen leads can be seen along with brash (small floating fragments) ice and frazil (gray slush) ice.

During the last three decades, there has been a great increase in man's interest in sea ice, a little studied material that covers roughly 13 percent of the surface of the world ocean. The main reason for this increased interest is very practical. Whenever we attempt to exploit advantageous aspects of the polar regions — for instance, to utilize shorter sea routes or to find increasingly rare mineral resources — sea ice looms both as an operational impediment and, if proper precautions are not taken, as a serious hazard to life and equipment.

However, beyond such practical considerations, sea ice has several other geophysical roles of considerable interest. It is an extremely sensitive indicator of climatic change; its presence causes a drastic change in the albedo* of the sea surface (from 0.1 for open water to as high as 0.85 for ice), resulting in a major change in the radiation budget; and it serves as an effective insulating layer between the warm ocean and the cold air (heat loss through open water is roughly 100 times the value through thick ice). It also provides an effective mechanism for exporting cold in the form of the latent heat of freezing out of the polar regions (a 1-meter-wide section of 1-meter-thick sea ice drifting toward the equator at 1 centimeter per second exports 3 x 10^6 watts); it changes the nature of the stress transfer between the atmosphere and the ocean; and in ways not well understood, exerts a major control on the stability of the oceanic mixed layer and influences storm systems moving along the ice edge.

What would we like to know about sea ice? Table 1 shows the problem areas and the ice characteristics associated with each. Condensing this list we end up with nine "icy" items:

- *Ice extent.*
- *Ice type.*
- *Ice thickness distribution.*
- *Ice drift velocity.*
- *Internal ice stress.*
- *Ice properties.*
- *Ice roughness.*
- *Ice growth and melting rates.*
- *Snow cover.*

To measure *extent,* we must be able to tell ice from water. By *type,* we are primarily referring to first-year ice, as compared with multiyear ice (ice that has survived at least one summer's melt season). This is an important factor as this difference is usually associated with an appreciable change in both thickness and properties (multiyear ice is thicker and less saline). *Thickness distribution* specifies the fraction of the region covered by ice in various thickness categories. Since one of these categories includes open water, the ice thickness distribution also gives us the ice concentration (the percentage of the area that is covered by ice of any type). Peak *ice drift velocities* as high as 4 meters per second have been observed and daily ice drifts of 25 to 30 kilometers are not rare. The *internal ice stress* refers to the stress exerted on a given volume of ice by the surrounding ice. In close pack ice, such stresses can be transferred over distances of hundreds of kilometers. A number of the many physical *ice properties* are interesting, particularly the mechanical and electrical ones. These properties are highly variable with both season and ice type. The *ice roughness* is controlled by two factors: the formation of pressure ridges produced by deformation and the rounding of any existing ice topography as the result of summer melt. As we can see the upper surface of the ice, we have a good feel for the nature of its roughness. Information on the roughness of the bottom of the ice is very limited. *Ice growth and melting* results in the gradual change in the nature of the ice thickness distribution which in turn is important in controlling the gross properties of the ice. Finally, the *snow cover* is an effective thermal insulator that affects ice growth. The presence of large amounts of snow also causes an increase (up to fourfold) in the friction between interacting ice floes and between ice and man-made structures.

What are some obvious difficulties that must be surmounted if we are to adequately characterize the world's sea-ice cover? First, the area is very large: the region covered by sea ice each year is more than four times the area of the continental United States. Only a tiny fraction of this area is quasi-static, with the majority of the ice moving as the result of forces exerted by wind, current, and neighboring ice floes. Typical movements vary from a few hundred meters a day to as much as 50 kilometers. Associated with these movements, leads* open and close, pressure ridges and rubble fields composed of randomly arranged ice blocks form, and floes rotate. At times, major changes in the icescape occur within a few hours. The leads and deformed ice make travel over the ice surface difficult and at times hazardous. Not only is the ice ever changing, but it also is shrouded by long periods of darkness (the polar night) as well as by clouds, fog, and blowing snow. In short, our task is imposing: we need to obtain detailed images of large areas of ice at frequent intervals under all weather conditions, clearly a challenge for remote sensing.

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*The fraction of the incident energy that is reflected by the body.

*A navigable passage through floating ice.

Table 1. Ice parameters of importance in different operations and research areas.

Area of Interest	Pertinent Ice Parameters*
Offshore operations	Extent, type, thickness, drift velocity, internal stress, properties (air temperature, atmospheric pressure, wind velocity, current velocity)
Climate	Extent, thickness
Albedo	Extent, type, snow cover
Insulation	Type, thickness, snow cover (air temperature, wind velocity)
Latent heat export	Thickness, drift velocity
Surface stress	Drift velocity, top and bottom ice roughness (wind velocity, current velocity)
Ocean mixed layer	Ice growth and ablation rates, drift velocity (current velocity, water-column stability)

*The parameters in parentheses are also important, although they are not directly related to ice.

A simple consideration of the scale, the requisite positional accuracy, and the desired sampling rate leads us to the conclusion that the remote-sensing systems of interest will undoubtedly be satellite-borne. Aircraft-borne systems are also useful, and will continue to be so in the future. However, in this article, we will stress applicable satellite systems when they exist or could reasonably be expected to exist.

Sea and Lake Ice

Why make a distinction between sea ice and lake ice? Many problems, at least on larger lakes, would appear to be similar to those of the sea. This is true enough, but from a remote-sensing point of view, sea and lake ice are very different. This is not immediately apparent: when we look at both ice types, we usually do not see the ice layers, but instead a thin 10- to 50-centimeter-thick layer of snow composed of reasonably equant,* randomly oriented ice crystals with dimensions varying from 0.4 to 1 millimeter and porosities between 45 and 70 percent. Lake ice is composed of the same materials as snow — that is, ice and gas, but the arrangement is different and the porosities are much smaller (at most 5 percent). The ice crystals are large, characteristically several centimeters to several tens of centimeters; they are columnar in shape, and they show strong crystal alignments. Most important, the ice contains numerous air bubbles, most of which show pronounced vertical elongations.

Ice itself is a low-loss dielectric* with attenuation distances (the distance over which the signal strength drops to $\frac{1}{e}$ [−0.37] of the initial value) on the order of several meters, depending on frequency. The air bubbles act as scatterers with the elongated bubbles serving as forward scatters (the scattered radiation continues in the same general direction as prior to scattering). For active microwave systems, the return is influenced by several factors. These are the roughness of the upper ice surface (rough surfaces, such as those produced by ridges, give strong returns), the scattering by bubbles within the ice, the roughness of the lower ice surface (the ice-water interface), and even whether or not the ice is frozen to the lake bottom. Passive microwave systems sense both the upwelling radiation from the water beneath the ice and the attenuation/emission from within the ice column.

The physics of the freezing process for seawater — 30 to 35 parts per thousand (‰) salts — is very different from that of lake water (20 to 50 parts per million salts). Lake water freezes with a planar ice-water interface, resulting in complete rejection of the chemical impurities in the solution being frozen. Sea ice, on the other hand, freezes

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*Relating to a crystal having equal or nearly equal diameters in all directions.

*A substance in which a steady electric field can be set up with a negligible flow of current.

with a strongly dendritic* interface with interdendritic spacings of a fraction of a millimeter. Between the dendrites, large amounts of brine are trapped. Typical sea ice salinites are 10 to 15 ‰ for newly formed ice, 5 to 8 ‰ for 1- to 2-meter first-year ice and 0.1 to 3 ‰ for multiyear ice (as ice grows older, brine drains out of it, a process that is particularly effective during the summer when the surviving sea ice is flushed by melt water).

Sea ice is composed of pure ice and gas inclusions (just like lake ice), plus a myriad of tiny liquid inclusions of brine, which is a high loss material. The result is that most sea ice is an extremely lossy material with attenuation distances of at most a few centimeters at microwave frequencies. Therefore, as there is very limited penetration of the radiation from active sensors into the ice, only the geometric characteristics of the upper surface matter. For instance, flat ice gives a very low return to active sensors because outgoing radiation hits the ice and is reflected away from the receiver. There is no scattering within the ice to cause radiation to return to the receiver. Ridges and other forms of rough ice though are strong reflectors because their irregular blocky surface results in a strong signal returning to the receiver. For passive sensors it is only the state of a thin, near-surface layer of ice that is sensed. Direct radiation from underlying seawater is not a factor as it is effectively absorbed by the ice even if the sea ice is very thin. The effect of the seawater is indirect in that, all other things being equal, the upper surface of thin ice is warmer than the upper surface of thick ice since it is physically located a shorter distance above the warm underlying seawater.

There is one important exception to this discussion of the lack of penetration of radiation into sea ice. There is penetration of radiation into multiyear ice, even at microwave frequencies, as a result of the fact that the brine has been flushed out of the upper (above sea level) portion of the ice. This flushing and refreezing process results in large numbers of gas bubbles within effectively fresh ice. Many of these bubbles are spherical and act as isotropic scatterers resulting in a measurable return at the sensor even if the upper ice surface is flat.

Let us briefly examine what the different types of remote sensing systems can contribute to the study of sea ice.

Visual Systems

Two systems currently collect visual observations. The Landsat satellite utilizes a multispectral scanning system with four frequency bands. It has a resolution of 60 to 80 meters (although high-contrast linear features smaller than this can be observed, for instance the Alaska-Canadian Highway). Each image is map correct and has a ground coverage of 185 x 185 kilometers (actually, the data are collected as a continuous 185-kilometer-wide strip). In the polar regions, there is repetitive coverage of a given location (up to a maximum latitude of 81 degrees North) for 2 to 5 days followed by a 13- to 16-day gap. As the tape recorders on these satellites have not proved to be particularly reliable, data can be obtained only when the satellite is within line-of-sight of a receiving station. The most significant limitations of the system are that imagery is limited by darkness and by clouds and that even if viewing is excellent, images of a given location cannot be obtained at regular, short (2 days or less) time intervals. Nevertheless, the imagery has proved useful for studies of ice conditions at certain local areas (for instance, the flow of ice through the Bering Strait, or the movement of coastal ice around Point Barrow, Alaska). Figure 1 shows an image from this system. Different features can be distinguished from one image to another, allowing the tracking of drifting ice floes.

The second system providing visual imagery is the Very High Resolution Radiometer (VHRR) on board the National Oceanic and Atmospheric Administration (NOAA) satellite series. Each swath is 2,350 kilometers wide and a location is imaged every day. As the orbit is near-polar, there are no latitude restrictions. However, the ground resolution at nadir is 800 meters and many important ice features are lost. Another problem, in addition to the limitations imposed by darkness and clouds, is that the image is displayed in a coordinate system that is awkward to use (it is good enough to map the movement of meteorological systems but not adequate for the smaller differential movements important in the drift of ice). Nevertheless, VHRR imagery has proved useful in monitoring the large-scale behavior of pack ice.

Thermal Infrared Systems

Thermal infrared (TIR) systems sense the temperature of the upper snow (or ice) surface. At first glance, it might appear that TIR could be used to indirectly estimate ice thickness since the surface of thin ice is warmer than that of thicker ice, with the warmest natural temperatures arising from open water in ice-free leads and along the ice edge. Thin-ice areas do show up as warm targets, making it possible to rapidly delineate recently refrozen leads. However, once ice becomes thicker than 1 meter, the temperature differences are small and are readily obscured by variations in the thickness of the snow cover. Therefore, TIR cannot be used to separate first-year from multiyear ice during all seasons unless special image-enhancement techniques are used. Also, to the best of our knowledge, there have been no independent checks on the validity of these separations. An

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*A crystallized arborescent (tree-like) form.

Figure 1. Landsat image (band 7) taken March 22, 1973, showing the deformation of the offshore pack near Barrow, Alaska. The indicated array of points was established three days earlier on two nested circles with diameters of 33 and 79 kilometers, respectively. Image width is 185 kilometers. (From Campbell, Weeks, Ramseier, and Gloersen, 1975)

additional problem encountered with TIR imagery is the presence of clouds. They obscure sea ice, and also can be warmer or colder than the ice; at times, their identification is difficult. The advantage of TIR imagery, apart from the fact that it gives a view very different from that of visual imagery, is that it is not limited by darkness.

The most useful TIR system in orbit is the VHRR-TIR on board the NOAA satellite series. The swath width, resolution, and repeat interval are the same as for the NOAA-VHRR-visual imagery. The TIR imagery is commonly used for large-scale studies of ice extent and movement.

Passive Microwave Systems

Microwave systems have one great advantage over visual and TIR imagery — they are not affected by either clouds or darkness. The problems of passive microwave systems are lack of resolution and difficulty of interpretation. For instance, the Electrically Scanning Microwave Radiometer (ESMR) on Nimbus-5 and the Scanning Multifrequency Microwave Radiometer (SMMR) on Nimbus-7 have footprints (the size on the ground of each picture element or pixel) of approximately 25 kilometers. Within each footprint there are commonly several types of sea ice, plus open water. Therefore, the passive microwave signature for each pixel will be the average of the signatures (the so-called brightness temperatures) of the different elements within the footprint. These brightness temperatures (T_B) are, in turn, products of the physical temperature of the material and its emissivity. At the 19.35 Gigahertz (GH_z) frequency of the ESMR system, the brightness temperature of open water (about 140 degrees Kelvin) is very low relative to that of ice. Therefore, sea ice and sea water can easily be differentiated and ESMR and other passive microwave systems have proved to be very effective in mapping the variations in the large-scale extent of sea ice in both polar regions. In addition, if only one ice type is present, a single frequency system, such as ESMR, can be used to map the percentage of open water within the ice pack. Figure 2 shows the compactness (the areal percentage of ice) and the extent of the pack ice around the Antarctic on December 26, 1972. Such a procedure is possible as Antarctic multiyear ice shows a microwave signature similar to first-year ice because very little melt is experienced during the Antarctic summer. In the north, however, multiyear ice is extensively modified by melt processes and shows a lower brightness temperature (about 215 degrees Kelvin) than first-year ice (about 240 degrees Kelvin). When such multiyear ice is present, a single frequency microwave system will give ambiguous estimates of the percentages of ice and open water.

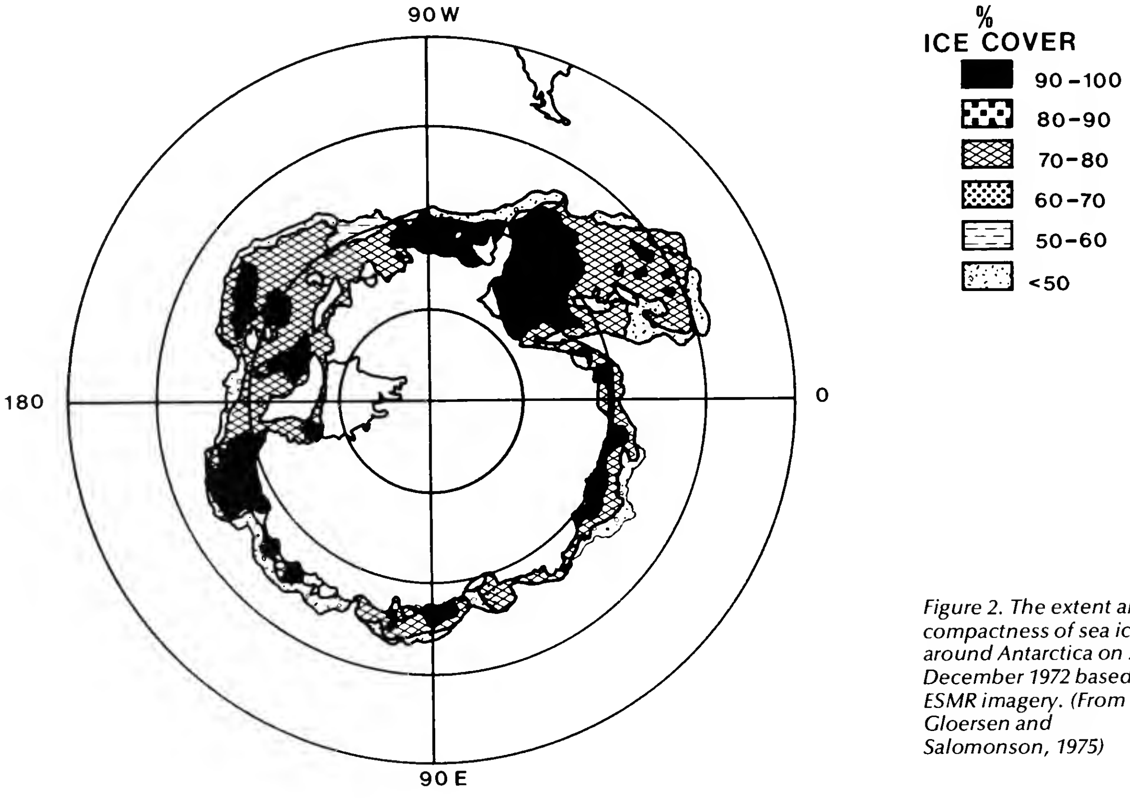

Figure 2. The extent and compactness of sea ice around Antarctica on 26 December 1972 based on ESMR imagery. (From Gloersen and Salomonson, 1975)

It is hoped that the multifrequency SMMR data will largely eliminate the ambiguities in the single-frequency ESMR data and provide daily hemispheric images specifying both sea ice types and concentrations. This work is still under way. The only anticipated problem is that the natural variation in ice signatures caused by emissivity and temperature variations coupled with electronic noise on the different microwave channels may still be high enough to cause uncertainties to remain in the analysis.

As mentioned earlier, the other problem with passive microwave is the large footprint. Ideally, it would be useful to have a footprint size of 1 kilometer or less so that the imagery would be readily comparable with data from other systems. In principle, this is easy to accomplish; in practice, it is quite difficult since high resolution requires a very large antenna built to exacting standards. However, even in the unlikely event that present passive microwave systems cannot be improved, such systems will continue to be extremely important tools in the study of sea ice.

Active Microwave Systems

The most promising of the several different active microwave systems that have been used in the study of sea ice is synthetic aperture radar (SAR). To achieve the resolution desired from a spacecraft-borne radar system, we need a large antenna. The expression *synthetic aperture* refers to a technique by which digital signal processing is used to numerically (synthetically) create a much higher azimuthal resolution than would be expected from the actual size of the antenna. Therefore, in a SAR system, the factor limiting the resolution is not the antenna size, but the problem of handling the extremely large data flow rate demanded by such a procedure. The advantages of SAR are many. It is independent of weather and darkness and provides a high-resolution image that can be made map correct. It also provides a very different view of sea ice that is easy to interpret.

To date, there has been only one deployment of a SAR system in a satellite — the L-band (wave length of 25 centimeters) SAR on Seasat. Even though this satellite failed after three and a half months as the result of a fault in the power supply, the data are more than adequate to demonstrate both the power and the problems of SAR. The system imaged a 100-kilometer swath 20.5 degrees off nadir at a resolution of 25 meters on the ground. Figure 3 shows a view on October 4, 1978, of the pack ice in the Beaufort Sea at a site just west of Banks Island in the western Canadian Archipelago. To interpret this image, we must remember that even at L-band frequencies there is little penetration of the radar pulse into the ice. Essentially the radar return is largely controlled by the nature of the upper surface of the ice. If the ice is rough because of ridging, there is scattering and a strong return is received at the satellite, which results in a bright image. If the ice is smooth, there is also a strong return, but the energy is reflected away from the spacecraft, resulting in a dark image. Unfortunately, if the open ocean is rough because of waves or smooth during a period of calm, strong and weak returns also result. Therefore, it may be difficult to distinguish open water from ice on the basis of the strength of the return alone. Fortunately, in most cases, the patterns of the areas in question and differences in the nature of the radar return between different satellite passes will usually allow a trained observer to separate smooth sea ice from smooth seawater and ridges from waves.

As is clear from Figure 3, there are many features in pack ice that are distinctive (shapes of floes, patterns of leads, and ridged areas). Experience with Seasat SAR imagery shows that many such features can be identified on sequential images over periods of weeks. Couple this capability with the fact that recent improvements in the processing of Seasat imagery allow us to specify the positions of pixels in the SAR imagery from open ocean sites with a RMS* positional error of 250 meters (if land points occur in the image, the error is commonly less than 100 meters; a value comparable with the positioning uncertainty of current drifting data buoys). Therefore, SAR has great potential in studies on the drift and deformation of pack ice.

The problems of the Seasat SAR were several. The processing was extremely slow (it took effectively 3 years to process 3 months of data), the data flow rate from the satellite was so high that observations could be obtained only if the satellite was within line-of-sight of a receiving station, and, at L-band frequencies, discrimination between first-year and multiyear ice was usually impossible.

What improvements would be possible if a new satellite SAR system were deployed? Much more rapid image processing should be possible with turn-around times of 3 to 6 hours. In fact, it would also be possible to transmit a degraded real-aperture image in real-time to operational sites, such as ships transiting pack ice or operating along the ice edge. This would aid ice navigation tremendously. It also should be possible to obtain a much wider swath (say 200 to 300 kilometers), which would greatly improve coverage. Finally, by going to higher frequencies (C or X-band, 2.5- to 7.5-centimeter wavelengths), we should be able to improve the discrimination between first-year and multiyear ice by obtaining enhanced volume scattering from the air bubbles in the relatively salt-free upper portion of multiyear ice. The problem with data storage will remain. SAR,

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*Root mean square.

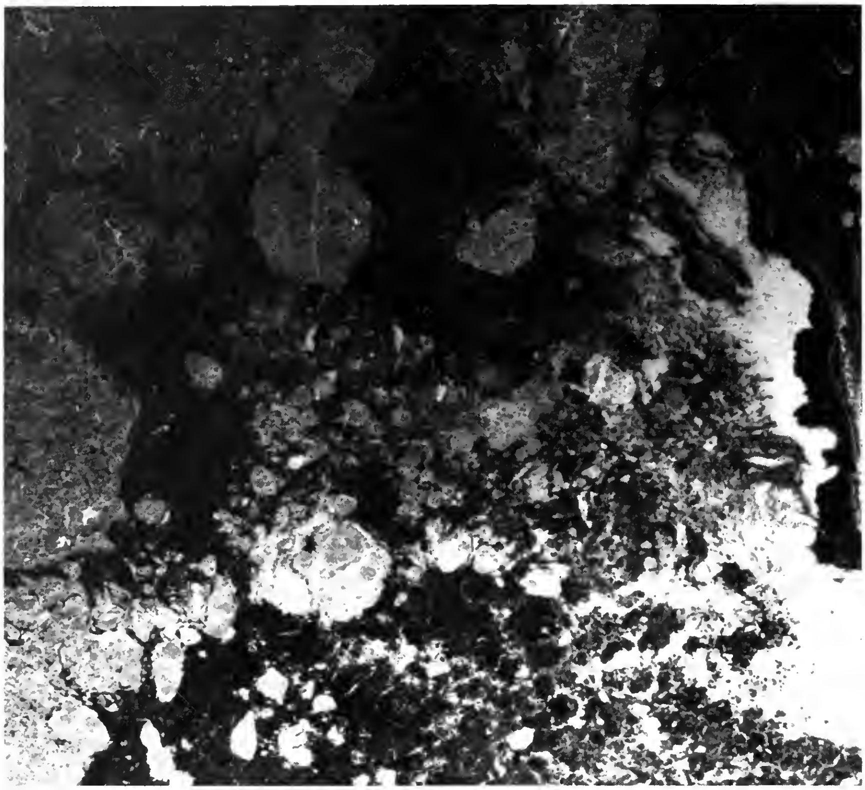

Figure 3. Seasat SAR image of sea ice on October 4, 1978, in the Beaufort Sea just west of Banks Island, N.W.T. Note the well-developed, large floes in the western part of the imagery. The image width is 100 kilometers. The dark areas are believed to be largely composed of flat, undeformed first-year sea ice. The uniform bright area running north-south in the eastern portion of the image is the result of sea clutter. (Courtesy Jet Propulsion Laboratory)

however, can make a definite contribution to our understanding of sea ice.

There are two other types of active microwave systems — radar altimetry and scatterometry. A radar altimeter (deployed on Geos-3 and Seasat) is a nadir viewing instrument that measures the height of the satellite above the ice surface with a precision of a few centimeters. In present systems, it has a footprint of 2 x 7 kilometers. As the nature of the returns from ice are quite different from those obtained over open water, altimetry data can be used to fix ice-edge locations to within a few kilometers and can be correlated with mathematical models to specify the ice roughness. One problem is that the return from undeformed ice is so large that the additional contribution as a result of ridging is very small. Such altimeters also measure both sea state and wind speed in the open ocean and supply sea-surface topography that is of interest to ocean dynamicists.

A scatterometer is a calibrated, downward-looking airborne radar that measures the backscatter coefficient of the underlying surface. Therefore, it also can be used to determine sea-ice boundaries and surface roughness. As the instrument normally views at angles off nadir, the percentage of the signal associated with the ice roughness is higher than is the case with the radar altimeter, a desirable situation. Scatterometry also can be used to discriminate between first-year and multiyear ice as well as to estimate surface wind velocities over open water. In Seasat, the scatterometer measured backscatter over a 1,500-kilometer swath with a resolution of 50 kilometers.

All three active microwave sensors are clearly powerful tools for the study of sea ice. Because of its map-like presentation, SAR appears to be the most useful, followed closely by scatterometry. Ultimately, it should prove possible to combine all three measurements into one that simultaneously collects all three sets of information.

Challenges Remain

At the beginning of this article we listed nine "icy" terms and discussed existing satellite-borne remote-sensing systems that could measure some of them. Now we should mention the items we cannot measure and point out why.

Although we can get some insight into the thin end of the ice thickness distribution by infrared sensing, there is as yet no way to directly measure ice thickness from space. The problem is how to get sufficient penetration into the lossy sea ice to get a return from its lower surface while maintaining a small enough footprint to be meaningful. Even with a surface or near-surface system this can be done only if the sea ice contains little brine. A space-borne system does not seem likely in the near future.

We encounter the same problem in measuring ice properties. To sense properties, we must penetrate into the ice. Again, some limited information on properties can be inferred from the fact that we can discriminate first-year from multiyear ice. Systems deployed on the ice surface (for instance, pulsed radar systems) can determine crystal orientation, but space systems do not seem likely in the near future. (It also should be noted that although satellite systems capable of measuring thickness and properties do not exist for lake ice, they should be much easier to develop than for sea ice.) The problem with sensing the snow cover is its low density and transparency at operational wave lengths. Some information, however, can be obtained from the visual systems, weather and darkness permitting. We can determine half of the information required to make rough estimates of ice growth rates by determining the ice surface temperature by infrared sensing. To complete the job, we would need to know ice thicknesses and, if possible, snow cover — both still are missing ingredients.

What does this leave us? Actually a great deal. We can directly observe ice extent, ice movements, ice roughness, and certain aspects of ice thickness at frequent intervals under all weather and lighting conditions. And we have stressed what individual instruments would do on their own. In fact, in any satellite sea-ice program several instruments would undoubtedly be used. For instance, a SAR, a passive microwave system, and a scatterometer would make a particularly attractive combination in which the sum of the combined results would far exceed the individual capabilities of the component systems. In Figure 4, we show how ice types can be differentiated by using combined results from a passive microwave system and a scatterometer. In addition, some of the same instruments also will provide observations on wind speeds and wave heights in the open ocean along the ice edge, items of great interest to investigators studying the behavior of the ice edge. We also could indirectly measure internal ice stress by deploying data buoys on the ice equipped to measure several levels of currents beneath the ice. These results — coupled with atmospheric pressure, air temperature, and wind velocity observations — could then be sent back to interested scientists via existing satellite data transmission systems.

In short, the capability exists to deploy satellite systems that would supply large amounts of critical information on sea ice essential to both the

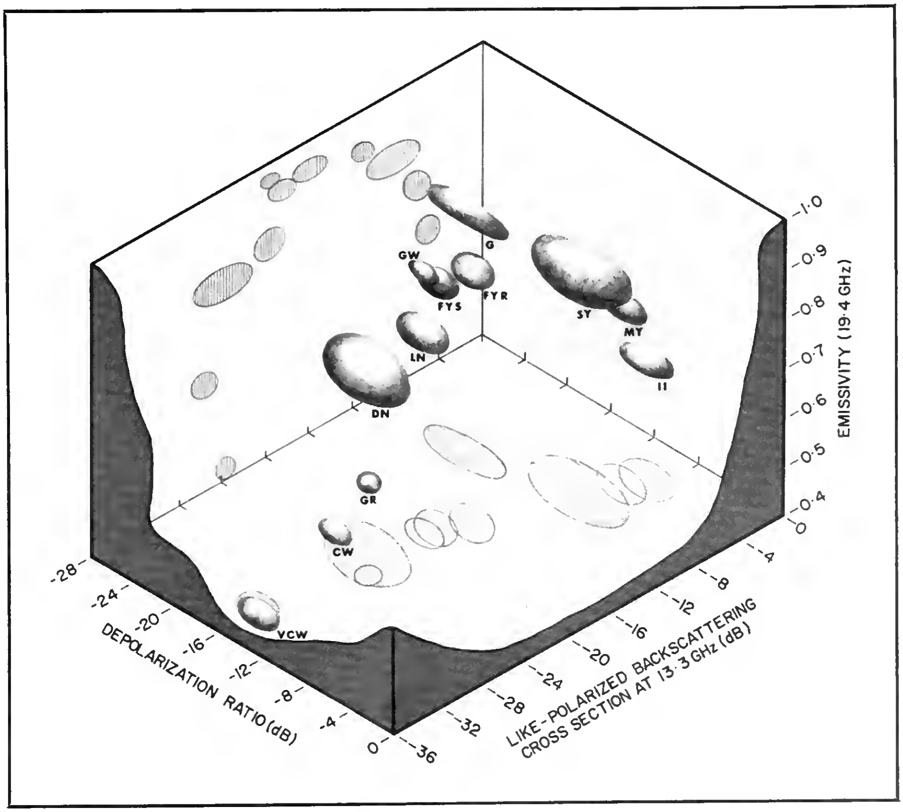

Figure 4. The classification of sea ice using data collected by a 13.3 GHz dual-polarized fanbeam scatterometer and a 19.35 GHz horizontally polarized profiling radiometer. The letters indicate different ice types: G, gray ice; GW, gray-white ice; DN, dark nilas; LN, light nilas; FYS, first-year smooth; MY, multiyear. (From Hawkins and others, 1981)

operational and scientific communities. There are many aspects of our knowledge of the remote sensing of sea ice that could be improved. However, we know that present systems could help resolve many pressing sea ice problems. It would be a far better strategy to deploy a system to undertake an operational demonstration of these real capabilities and build a research program around this deployment than to continue research that only fine-tunes hypothetical systems that never seem to become reality.

There have been many claims about the marvels of remote sensing in resolving sea ice problems. Many of these claims could become true. It is time for the remote-sensing community to take action and actually deploy such a system. When this happens, sea-ice remote sensing will make the transition from a toy being enjoyed by a few to a tool being used by many. The present situation is somewhat similar to a poker game in that every so often you have to put some money on the table or players will not take you seriously. Unfortunately, under the present funding and political climate, such an ante from the United States side of the game does not appear likely.

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Suggested Readings

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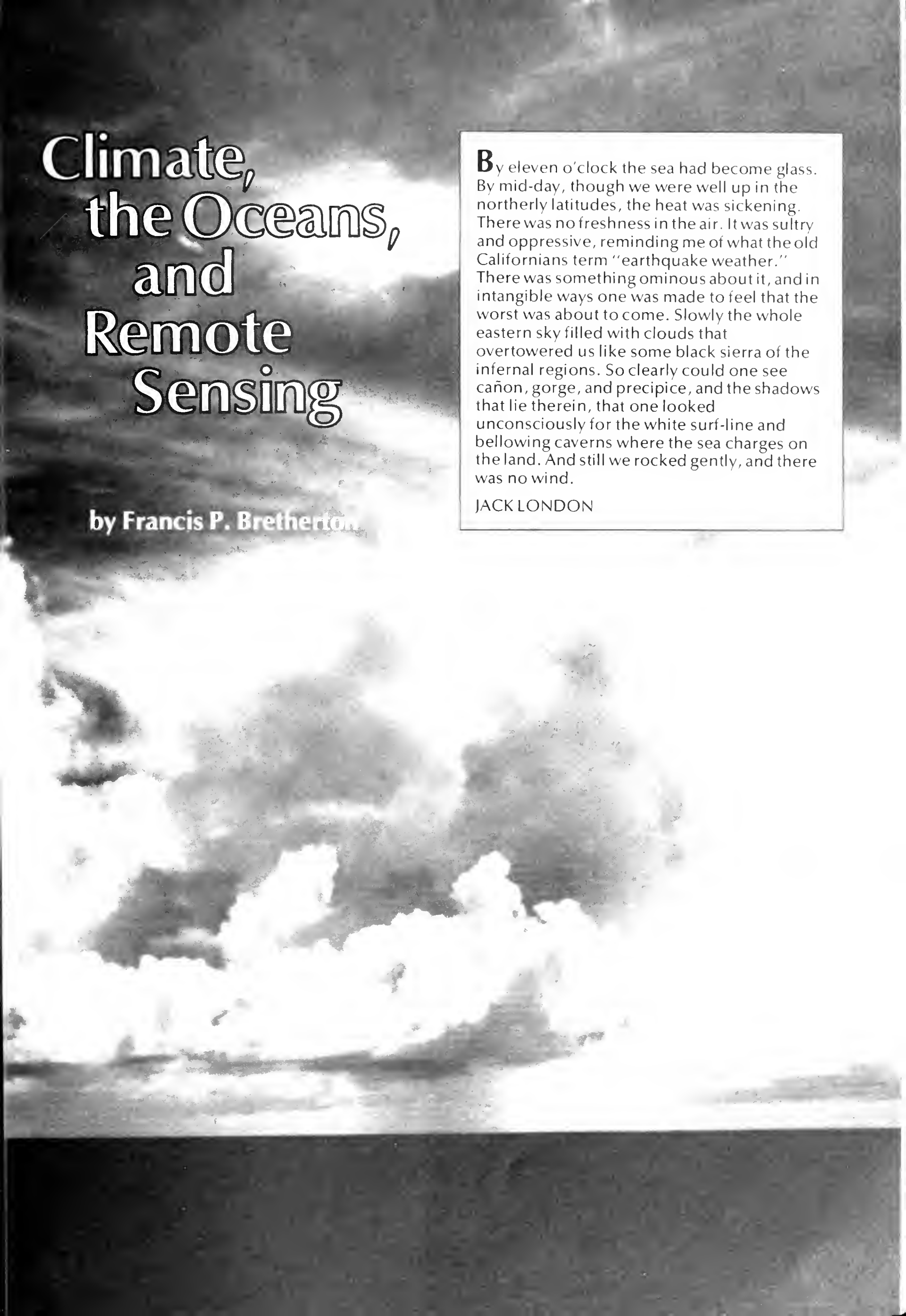
(Photo by Jan Hahn)

Climate, the Oceans, and Remote Sensing

by Francis P. Bretherton

> By eleven o'clock the sea had become glass. By mid-day, though we were well up in the northerly latitudes, the heat was sickening. There was no freshness in the air. It was sultry and oppressive, reminding me of what the old Californians term "earthquake weather." There was something ominous about it, and in intangible ways one was made to feel that the worst was about to come. Slowly the whole eastern sky filled with clouds that overtowered us like some black sierra of the infernal regions. So clearly could one see cañon, gorge, and precipice, and the shadows that lie therein, that one looked unconsciously for the white surf-line and bellowing caverns where the sea charges on the land. And still we rocked gently, and there was no wind.
>
> JACK LONDON



The three-quarters of the earth's surface covered by ocean is poorly observed, yet it dominates the overall behavior of the climate system. Thus earth-orbiting satellites offer us a unique opportunity in that we can observe the globe as a whole. But since the only means of contact through the vacuum of space is by electromagnetic radiation (light, radiant heat, and radio waves), the methods of these satellite-based measurements usually must be somewhat indirect. We must carefully examine just what the potential for remote sensing from satellites really is, in terms of our understanding year-to-year climatic fluctuations and how the whole climate system really works.

There are four main areas of concern: 1) the yearly progression of seasons that makes up the annual cycle, 2) year-to-year fluctuations, such as those associated with droughts or severe winters, 3) the role of the oceans in maintaining the long-term pattern of climate, and 4) the potential changes in climate resulting from man's activities over the next hundred years or so. To study these aspects of climate, we will need to use computers for very complex calculations, in-situ observations from ships and other platforms in the ocean, and remote sensing from satellites.

The Annual Cycle of Climate

In our determination of the set of typical temperature and weather patterns that we call climate, the most obvious role of the ocean is as a store of heat and moisture for the atmosphere. Excess heat from the sun in summer is retained by the upper few hundred meters of the ocean and returned throughout the year to the air masses above, mostly in the form of latent heat associated with evaporating water. When this vapor condenses and returns to the surface as rain, the net effect is to warm the atmosphere to a temperature that is similar to that of the underlying ocean. The large heat capacity of the ocean has a major moderating influence on the annual cycle of climate, not only in coastal regions but also throughout the adjacent continents, because of the prevailing flow of the upper air.

Figure 1 shows the variation with latitude and season of the net radiation at the top of the atmosphere, as measured from polar-orbiting satellites. The net radiation is the difference between the incoming heat from the sun, which is mainly visible light, and the outgoing heat from the earth, which is partly visible light reflected back from clouds and land surfaces and partly visible infrared radiation emitted by the earth (including the ocean) and the atmosphere above it. Except for a narrow band of latitudes around the equator, there is a strong annual cycle, opposite in the northern and southern hemispheres. Averaged over the whole globe, the net radiation must in the long run balance to zero. Otherwise, the earth would be steadily warming up. Figure 1 shows the rate at which heat is being taken up by the ocean in the short run, less a relatively small amount redistributed to other latitudes within the atmosphere. Because the surface layers of the ocean are continually stirred by the wind, they can absorb this heat for a six-month period while changing their temperature by only a few degrees Celsius. This is in contrast to land surfaces, which warm up rapidly. Because of the strong dependence of direct cooling and evaporation on the air-sea temperature difference, the temperature in the lower part of the atmosphere cannot depart very much from the sea-surface temperature for more than a few days, exercising a strong control over the whole atmospheric circulation.

In describing and understanding this process, we need to know the total amount of heat stored, the sea-surface temperature, and the wind stress that stirs the ocean and mixes the heat downward, distributing it over a larger mass of water and therefore reducing the temperature changes. Observations are needed over very large areas for many years. Data on the sea-surface temperature and wind speed are available from

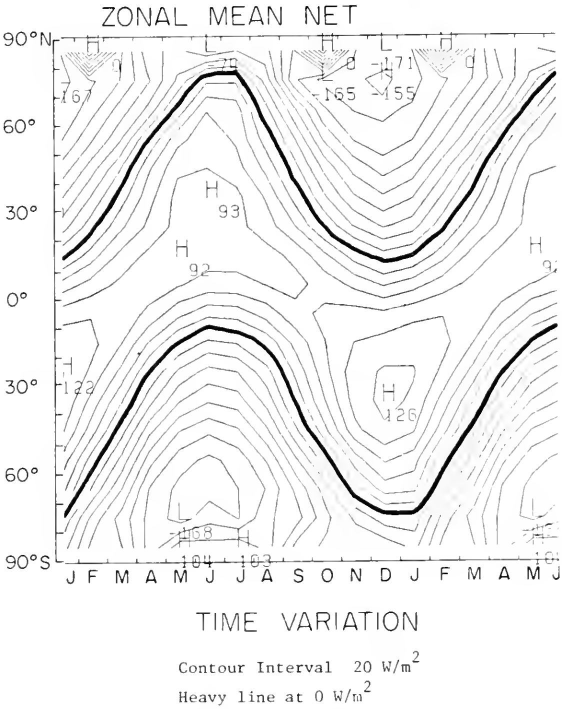


Figure 1. Satellite measurements of net radiation per unit area at the top of the atmosphere, as a function of latitude and time of year. Net radiation is the difference between the incoming energy from the sun and the sum of the reflected solar energy and that emitted by the earth. (From J. G. Campbell and T. H. Vonder Haar, 1980)

merchant ships, but there are large gaps in the coverage and the accuracy is uncertain. Consistent, well-calibrated measurements from a few instruments on a satellite that covered the globe every day or so would be extremely valuable. Unfortunately, since the ocean is opaque to electromagnetic radiation, measurements of the heat stored below the surface could not be obtained in this way, but there is still a major role for satellites in telemetering data obtained from buoys floating on the surface and trailing subsurface instruments.

Year-to-Year Climatic Fluctuations

Most people and their economic activities are well-adapted to the average annual cycle of climate in any particular location, based on long experience of the conditions to be expected during various times of the year. Thus, of particular importance are the year-to-year departures from these expectations, particularly extremes such as droughts or abnormally severe winters. These variations are normally associated with widespread fluctuations in seasonal weather patterns, and anomalies in ocean heat storage and surface temperature. Whether the ocean is responding to changes in the atmosphere or instead is driving them, is a somewhat controversial issue, but a vital one if observations of such anomalies are to be used for climate prediction.

By looking at the effects of sea-surface temperature changes on the atmospheric weather patterns (as seen on computer models) and from analyzing the progression with depth and time of observed temperature fluctuations in the ocean, we find that in the mid-latitude eastern North Pacific the anomalies in surface temperature are mainly the result of previous patterns of wind and cloudiness and have relatively little impact on future weather over North America. On the other hand, analysis of many years of meteorological data discloses a characteristic sequence of major changes in the rainfall patterns in the equatorial Pacific, with associated changes throughout the tradewind zone and significant correlations with wintertime temperatures in the southeastern United States and certain other mid-latitude regions. This sequence appears irregularly at intervals of 3 to 7 years, and is apparently triggered by anomalies in sea-surface temperature close to the equator in the central Pacific. These changes are shown in Figure 2 as areas of high and low atmospheric pressure extending poleward from the source anomaly (shaded). It has

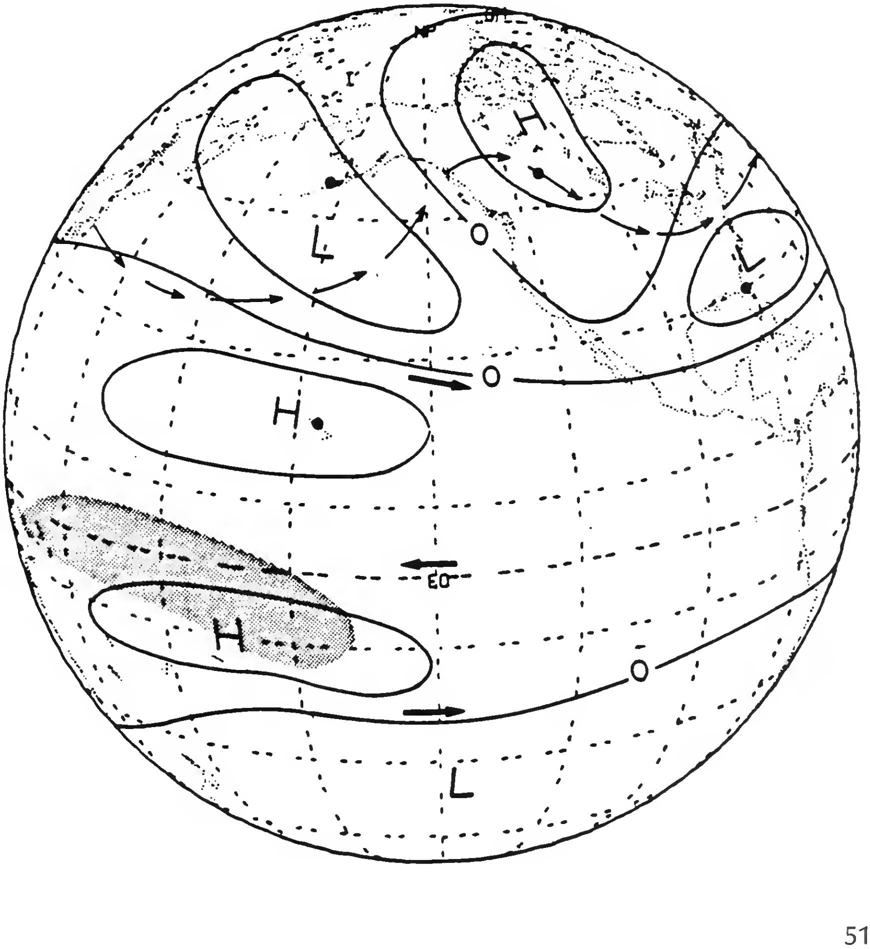


Figure 2. Changes in atmospheric pressure associated with an anomaly in sea-surface temperature (shaded) in the equatorial Pacific. (From J. B. Horel and J. M. Wallace, 1981)

been proposed that these anomalies are connected with the El Niño phenomenon (see *Oceanus*, Vol. 21, No. 4, p. 40) near the coast of Peru, but the dynamic mechanisms are still controversial. One theory is that wave-like oscillations of the near-surface ocean currents are initially excited by the wind but then propagate slowly westward. Such oscillations can be detected from changes in sea level. At present, suitable measurements are available only from a few scattered island stations, but they could be made everywhere from a carefully designed satellite system (see page 17). Such observations would permit a more definitive test of present theories and lay the basis for the possible prediction of future fluctuations.

Long-Term Heat Transport

A quite different role of the ocean in the climate system is the long-term transport of heat from one latitude to another by large-scale currents. Because of the large heat capacity of the ocean as a whole, this process is meaningful only when we are considering averages over decades or centuries, but current estimates show that the ocean is responsible for about a third of the transfer of heat from the tropics to temperate latitudes by the whole climate system. The remaining two-thirds is carried by the atmosphere. This transfer has a substantial impact on the temperature in high latitudes. An example is the systematic flow of warm surface water northward past the British Isles into the Norwegian and Labrador Seas, with a return at great depths and much colder temperatures. Estimating these effects quantitatively is not easy, but apart from direct measurements in the ocean itself, inferences can be made from the flow of heat through the ocean surface, and also from the time-averaged net radiation at the top of the atmosphere corrected for transfers from one latitude to another within the atmosphere.

Present techniques for calculating the flow of heat through the ocean surface depend on merchant-ship observations of variables such as clouds and atmospheric humidity. Such data are subject to considerable errors, and are very sparse in many parts of the world. In areas of relatively good coverage, such as the North Atlantic, maps of the heat flow have been prepared (Figure 3). Many of the map features are consistent with our qualitative expectations based on other information, but the magnitudes are not very reliable. From satellite pictures of cloudiness, we could estimate the amount of sunlight reaching the surface of the ocean.

Another, more speculative, application of similar data would be to estimate rainfall and atmospheric moisture transports. The difference

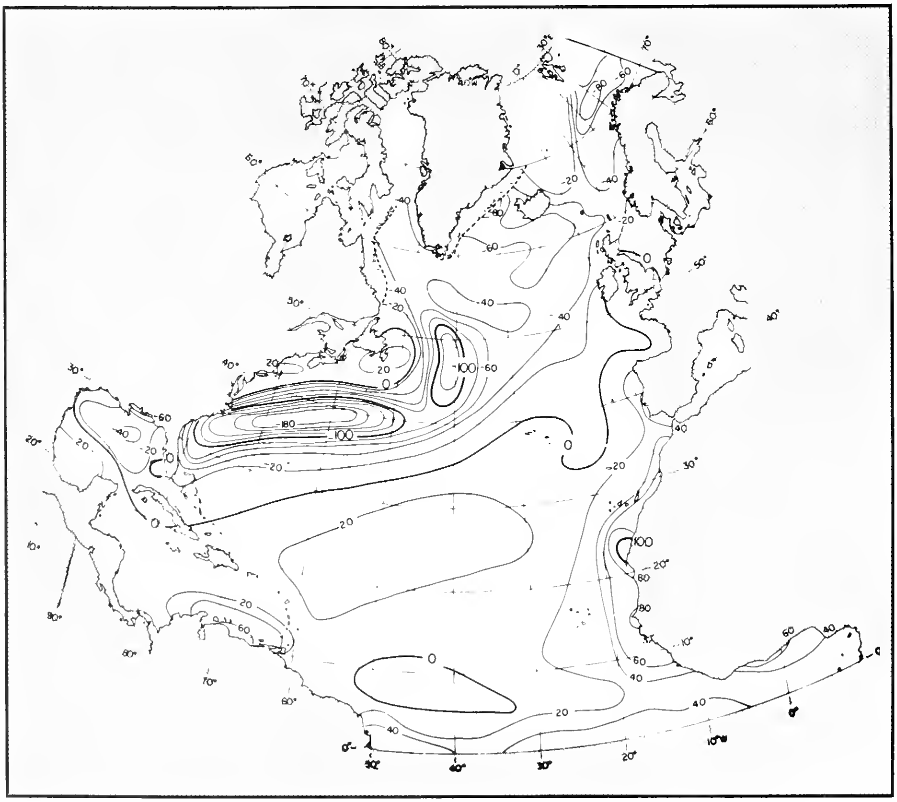


Figure 3. Net rate of heat loss from the ocean to the atmosphere in the North Atlantic. Note the large values above the relatively warm waters of the Gulf Stream. (From A. F. Bunker and L. V. Worthington, 1976)

between these variables gives the rate of evaporation from the ocean surface, which is the other key factor in the net flow of heat there. In this era of space technology, it is perhaps surprising that the major obstacle to this approach lies in the lack of a suitable in-situ instrument for measuring rainfall at sea, which could be used to calibrate the inferences from satellite observations. Under the conditions prevailing aboard ship, the conventional rain gauge, which is essentially a calibrated bucket, is almost useless, and no substitute has yet been found.

Warming by Carbon Dioxide

Another major role of the ocean in climate has to do with the increase in carbon dioxide concentration in the atmosphere (Figure 4). This phenomenon is the result primarily of the combustion of coal and oil that has occurred in the last 50 years, and it is likely to continue at even greater rates for the next hundred years or more. Increasing carbon dioxide makes the atmosphere more opaque to infrared radiation, which allows less heat to escape to space from the surface of the ocean or land, and eventually results in an increase of the earth's temperature. Many studies using atmospheric models have shown that a doubling of the present concentration of carbon dioxide would increase the equilibrium temperature averaged over the earth by 2 to 3 degrees Celsius, a little less in the tropics and probably twice as much in high latitudes. Such a change, combined with the present rainfall patterns, would have a substantial impact on agriculture and many aspects of the world economy and social structure. Because of the complexity of the system being modeled, the precise magnitude of these changes is uncertain to a factor of about two. Predictions of future carbon dioxide concentrations differ even more widely, being dependent on assumptions about economic growth and patterns of fuel consumption, on models of uptake by the ocean, and on storage or release from a changing distribution of peat bogs and tropical forests. However, most speculations imply at least a doubling at some time during the 21st century.

A recent issue in physical oceanography is the effect of the ocean's heat capacity in delaying the overall temperature rise. The crucial question is how much of the ocean would be involved and on what time scales. If isolated from the water below, the upper 50 meters would come to a new equilibrium within about 3 years following any change, whereas if the whole ocean were to warm up at the same rate, a new equilibrium would take 300 years. Clearly, the appropriate time lag is somewhere in-between, but a reliable analysis requires considerable information about the way in which water circulates in the ocean and the time it takes to do so.

We can obtain some information by observing the evolving distribution of radioactive substances, such as tritium, which were deposited at the surface of the ocean following the hydrogen bomb tests of the 1960s (see *Oceanus*, Vol. 20, No. 3, p. 53). Otherwise indistinguishable from water, tritium can be detected in minute concentrations, exposing the pathways for mixing and recirculating in the ocean. Since additional heat resulting from atmospheric carbon dioxide would follow similar pathways, some calculations can be made of the delays in coming to a new equilibrium. The time

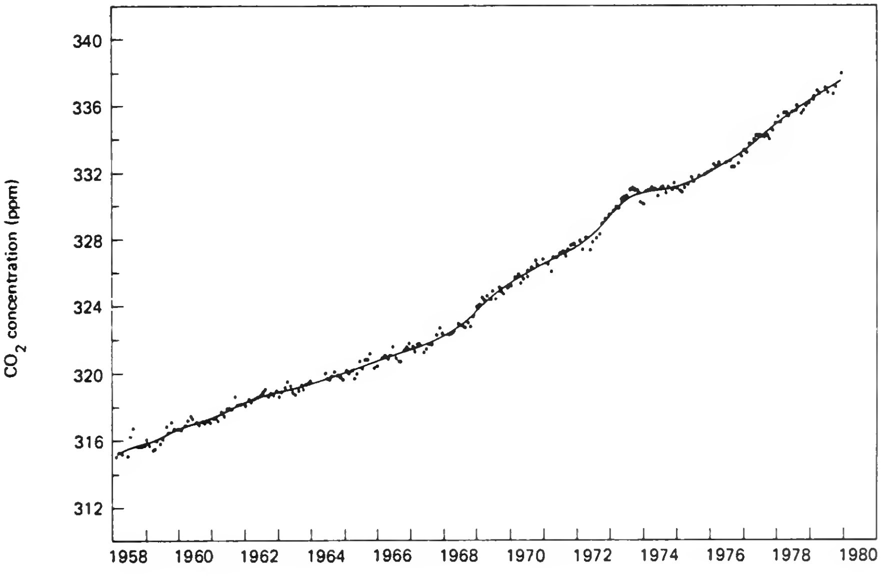


Figure 4. Concentration of atmospheric carbon dioxide (in parts per million) at Mauna Loa observatory in Hawaii. The annual cycle has been removed. (Adapted from Keeling)

involved is at least several decades, which is probably not long enough to reduce the overall trend to negligible levels.

A full analysis of these issues requires detailed observations of the circulation throughout the world ocean, the deep currents and density distribution as well as the wind stress and flow of heat at the surface. Interesting possibilities for obtaining this information include measuring minute changes in the speed of sound within the ocean and telemetering the data to land by satellite, or distributing thousands of floats that sink to a predetermined depth and move with the currents there for a few months or years, after which they return to the surface and are located by satellites.

Observing Techniques

Keeping track of the climate system requires many types of observations. In the ocean, the primary variables are temperature, salinity, and velocity at all depths and at sea level, together with the major driving forces, such as the wind stress at the surface, the temperature and flow of heat there, and the difference between evaporation and rainfall. Complete, reliable measurement of all these factors is a formidable task, and many approaches are being used to obtain at least partial information.

Probably the most important satellite-related measurements are those of wind stress from a scatterometer, sea level from an altimeter, and sea-surface temperature from one or more of the "windows" in the electromagnetic spectrum for which the atmosphere is relatively transparent. These techniques hold great promise, and considerable resources are being invested in them. However, none is yet a well-understood system that yields as its end product properly calibrated and sampled long-term measurements of the large-scale averages of these variables to the accuracy needed for definitive progress.

How to achieve a partnership of ocean scientists, space engineers, and specialists in large-scale data processing is one of the major challenges of the next two decades. The problems of building sophisticated instruments and operating them in space, and processing the very large volumes of data they generate, have been tackled with considerable success. Less attention has been paid to converting instrument readings which would lead to routine trustworthy measurements of the physical property under study.

For example, Figure 5 shows the correlation between measurements of wind speed as seen from a scatterometer aboard Seasat and nearby observations of wind speed that involve more conventional means. The agreement is encouraging, but discrepancies are such that further experience will be necessary before the measurement will be completely understood. The scatterometer observes neither wind speed nor stress directly, but rather the capillaries or ripples on the ocean surface with wavelengths of a few centimeters, averaged over a footprint (the instantaneous field of view of the instrument) some 25 kilometers across. These capillaries are familiar to sailing enthusiasts as the visible roughening of the sea surface which heralds an approaching gust of wind. However, the processes whereby they are generated are not well understood. Though empirical correlations of wind speed (or wind stress) have been established, the influence of factors such as variability within the footprint, swell, surface contamination, or even the temperature dependence of surface temperature has not yet been accurately assessed, nor are the techniques fully reliable for detecting contamination of the signal by rain. The potential is great, yet its fulfillment will require a comprehensive program aimed at verifying all aspects of system performance. This should include elucidation of the mechanisms for capillary generation and end-to-end intercomparison with the best possible in-situ measurements, not only in intensive experiments aimed at observations coincident in space and time, but also in comparisons of statistical distributions in selected regions, aimed at the averages and probabilities of extremes that are usually of most importance to climatologists.

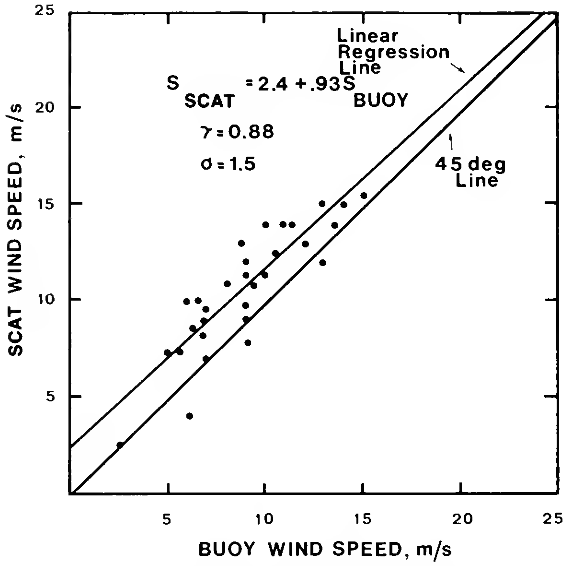


Figure 5. Relationship between wind speed as measured by the scatterometer aboard Seasat and observations from nearby buoys and ships on the ocean surface. (From the report on the Gulf of Alaska experiment, National Oceanic and Atmospheric Administration, 1980)

Another satellite measurement that has received considerable attention is sea level. So far, results have been disappointing, with errors in the operational products comparable to the natural variability of the large-scale anomalies of interest here. Though others take the opposite view, the opinion of the author is that, for climate purposes, at least, there remain reasonably promising satellite options that have not been tried and found wanting. These relate primarily to the selection of procedures for the routine processing of existing data streams. For a slowly changing variable like large-scale average temperature, continuous coverage is not necessary. Indeed, a few observations of known high quality may be preferable to many that contain systematic but unknown errors. Yet the basic data are obtained primarily for day-to-day weather forecasting, where timeliness, coverage, and ready assimilation are of paramount concern. These are certainly desirable features in research applications, but they are lower in priority than quality control, appropriate sampling, and consistent calibrations. The type of consideration that is central to much oceanography and climate research may carry little weight in the decisions made by the operational weather services about the routine processing of satellite data. The research community cannot assume that the existence of a suitable basic data stream means that its needs have been automatically met. Indeed, experience shows that without sustained effort by key individuals, the exigencies of the operational environment will prevent most of the needs from being met, and the value of the data base for research purposes will be severely degraded.

Conclusions

Understanding the workings of the climate system and learning how to predict year-to-year variations and possible long-term changes resulting from man's activities will require extensive observations of the ocean. The surface temperature and flux of heat through the surface are key variables for the atmospheric circulation. The wind stress on the surface and the net of evaportion less rainfall are also important drivers of the ocean circulation. The long-term redistribution of heat by the ocean currents and year-to-year fluctuations in heat storage are central climatic variables. Because of their global perspective, satellite observations may play a key role in many of these areas, though other important measurements will have to continue to be made from in-situ platforms, which often involve satellite communications and location capability. Though the promise is great, full realization will require a patient and imaginative collaboration among space engineers, data-processing specialists, and oceanographic scientists of diverse interests and experience, plus the evolution of new ways of sustaining programs and institutions over the many years needed for fruition.

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Commercial Applications

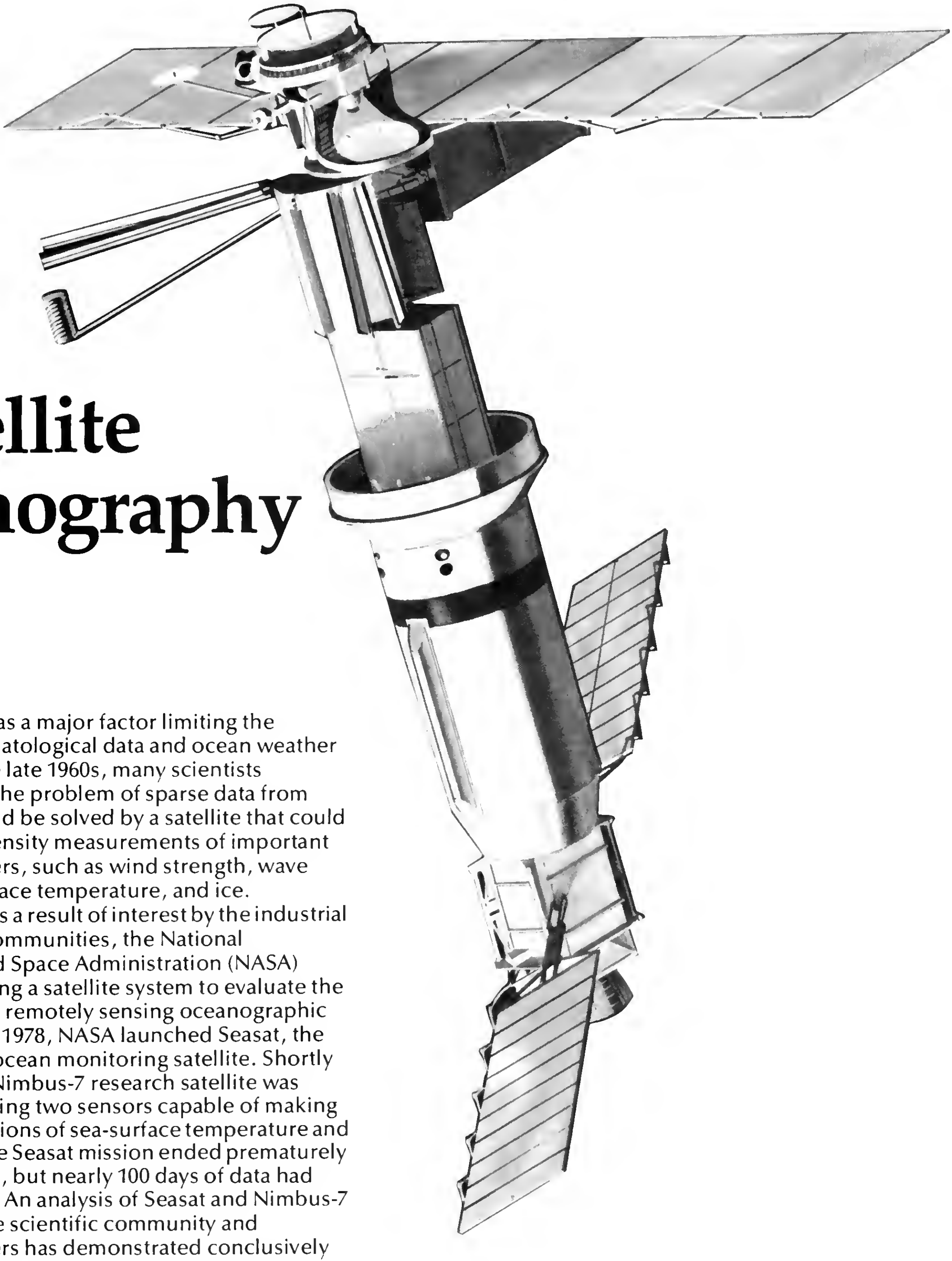
by D. R. Montgomery

Since the launch of Tiros I in 1960, satellites have revolutionized the collection of weather data. Observations of clouds are so extensive that it is virtually impossible for a major storm to go undetected; and satellite sensors are routinely measuring atmospheric profiles of temperature and moisture. Despite these technological advances, significant gains in the accuracy of meteorological and oceanographic forecasts have been hampered by the scarcity of good surface observations over ocean areas. Even though there are more than 50,000 ships with gross tonnage exceeding 500 tons, our national forecast centers receive fewer than 2,500 weather reports from these ships each day in near-real time, with the bulk of these observations concentrated along coastal regions and the major shipping routes. Few observations are obtained in vast areas of the oceans and in polar regions. National and international buoy systems augment total coverage to a minor degree, but it is generally agreed that the commercial ocean industry and our naval forces now suffer from inadequate data and forecasts related to the oceans.

More accurate environmental prediction requires larger and faster scientific computers, better models, improved ocean observations, and faster data collection and transmission to our national weather and oceanographic centers.

With the development of computer-based numerical models for the forecasting of ocean conditions and weather, it became apparent that the lack of information concerning oceans and

# of Satellite Oceanography



polar regions was a major factor limiting the accuracy of climatological data and ocean weather forecasts. In the late 1960s, many scientists suggested that the problem of sparse data from these areas could be solved by a satellite that could provide high-density measurements of important ocean parameters, such as wind strength, wave height, sea-surface temperature, and ice.

In 1973, as a result of interest by the industrial and scientific communities, the National Aeronautics and Space Administration (NASA) began developing a satellite system to evaluate the effectiveness of remotely sensing oceanographic phenomena. In 1978, NASA launched Seasat, the first dedicated ocean monitoring satellite. Shortly afterward, the Nimbus-7 research satellite was launched, carrying two sensors capable of making critical observations of sea-surface temperature and ocean color. The Seasat mission ended prematurely in October 1978, but nearly 100 days of data had been collected. An analysis of Seasat and Nimbus-7 data by both the scientific community and commercial users has demonstrated conclusively that wave heights, sea-surface directional wind velocities, and sea-surface temperature and topography can be measured from space.

This information can be used in marine industries to improve weather or sea-state-related operations; supply better warning of severe wind, rain, or wave conditions; provide a way to improve and manage the resource yield; provide improved navigation through ice and currents; and create a

At left, an Atlas rocket blasts the Seasat satellite into space on June 26, 1978. (Photo courtesy of NASA)

Above, artist's concept of Seasat in space. (Sketch courtesy of NASA) better understanding of the ocean and its dynamics. Table 1 delineates the broad applications of satellite oceanography to marine industries.

Commercial Benefits

Deep-ocean mining is an industry still in its infancy (Figure 1). Companies engaged in offshore mining are exploring a region of the equatorial Pacific, extending from the coast of Mexico to the Hawaiian Islands. Although this region has primarily benign weather for most of the year, hurricane storm tracks often cut through this area. Surveys indicate that many of the areas with the richest resource potential are not located in the major shipping lanes and thus are the most poorly observed by

Table 1. Possible oceanographic satellite applications.

Activity	Application
Offshore oil and gas	*Increased ocean forecast accuracy*
	Exploration operations
	Seismic surveys
	Drill ships
	Towout operations
	Production operations
	Crew scheduling
	Platform and crew safety
	Ice observations
	Ice dynamics for platform design criteria
	Ice movement for platform and crew safety
	Environmental data
	Replace platform instrumentation
	Subsurface and seabed dynamics
	Gas pipeline and applications
Environmental forecasting	*Increased observations (particularly in Southern Hemisphere)*
	Consistent observations
	Wave-height measurements
	Wind averages
Marine transportation	*Increased ocean forecast accuracy*
	Optimum routing
	Port scheduling
	Ice observations
	Arctic resupply
	Vessel/personnel safety
Deep-ocean mining	*Increased ocean forecast accuracy*
	Mining operations
	Improved tropical storm, storm-track prediction
	Mining operations and safety
	Historical data base
	Unbiased climatology
	Mining equipment design
	Operational criteria
Marine fisheries	*Increased ocean forecast accuracy*
	Efficient search efforts
	Efficient gear operations
	Reduced gear losses
	Crew and vessel safety
	Ice observations/forecasts
	Gear losses
	Crew and vessel safety

conventional means. The deep-ocean-mining industry is using wind and wave climatologies from ship reports in designing equipment and formulating operating plans and schedules.

One Seasat study shows that up to $1.8 million a day could be lost in production because of high waves in the operating region. Measurements of wave heights infer that wave climatology data for the ocean-mining region may be biased (low), and since equipment designs have been based on these climatological data, may result in smaller operating "weather windows." Should these narrower windows cause a 1 percent loss in a 250-day operating year, it is estimated that the yearly production loss would be about $4.5 million. Although this value is small compared with other economic uncertainties in mining operations, the existence of a better climatological design base, as available from satellite observations, could be used to improve the system design and minimize production losses from unanticipated high waves.

Satellite observations of the deep-ocean mining region offer the potential to predict severe storms with 10 hours warning and also the required calm weather windows of 57 hours duration. If sufficient advance warning of adverse weather and sea conditions is secured, and if the forecasts are accurate, ocean mining operators can elect to lift the miner off the bottom, maneuver so as to minimize ship motion, and ride out the storm on-station. Using this tactic, operators lose less operating time than they would if they had to flee the area completely because of a lack of information. Failure to obtain such a forecast can result in revenue losses of up to $1.8 million a day (and a loss of nearly $20 million if, for example, a pipe string is destroyed in bad weather).

Optimum ship-routing techniques that were developed in the 1950s by the U.S. Navy have been in use for about 15 years by the private sector. Ship routing is provided as a commercial service and is intended to minimize operating parameters such as transit time or fuel consumption, and reduce the exposure of the ship and its cargo to severe weather. It is estimated that about 25 percent of all ships over 5,000 tons utilize shore-based ship routing and/or en-route surveillance. The most important parameter in automated ship routing is sea state; however, winds, currents, and hazards to navigation, such as fog, rain, snow, and ice are also significant (Figure 2). Reliable sea-state analysis and predictions can reduce transit time up to 10 percent, resulting in savings of $15,000 to $40,000 for a typical Pacific voyage. Optimum selection of shipping routes needs better medium-range forecasts as well as improved ocean climatologies. Seasat studies conducted by a U.S. ship-routing company indicate that the use of satellite-derived wind observations can be useful in more accurately locating low-pressure storm centers. This knowledge could reduce vessel transit distances and times, with operating savings in the range of $1 to $3 million a year for selected vessels (through reduced ship and cargo damage and reductions in crew injuries).

Recent increases in the costs of natural gas and oil, together with a growing scarcity of these items in the more accessible regions of the globe, have given that industry incentives to explore the

Figure 1. Deep-ocean mining operations require accurate and timely warnings of severe tropical weather. (Photo courtesy of Deepsea Ventures, Inc.)

Figure 2. Ice and fog represent serious hazards to navigation in polar ocean regions. (Photo courtesy of Canadian Marine Drilling, Ltd.)

more remote and severe environments of the world (Figure 3). It has been difficult and expensive to acquire weather, oceanographic, and ice data in these areas. Offshore oil and gas operations are probably more expensive than any other ocean industry. Some new rigs cost $50 to $100 million and have daily lease costs in the range of $50,000 to $100,000. Also, this industry needs continuous, high-quality observations to monitor the local environment and provide the historical data needed for design improvement. Designers are "over designing" rigs to the cost of approximately $5 million apiece because of inadequate wind/wave data.

Environmental data are also important to the design and installation of pipelines on the seabed. Swells from distant storms and local water surges related to wind systems create currents that act on these pipelines. The safety of these installations is becoming increasingly important as larger diameter pipelines are being planned for offshore areas all around the world. Seasat has shown that an operational oceanographic satellite system could have an impact on the economics of the entire offshore oil and gas industry through better observations of wind, wave, temperature, current, and ice conditions.

Ice surveillance in Arctic (and Antarctic) regions provides information on ice coverage, extent, and movement, along with definitions of openings and leads. Such observations greatly aid the navigation of merchant ships in these regions and fishing vessels along the edge of ice sheets. The offshore oil and gas operators in the Arctic regions (Figures 4 and 5) are very watchful of ice, weather, and waves, since such environmental factors govern both facility design and the long-range, strategic, and tactical planning necessary for safe and efficient operations. It has been estimated that a significant percentage of aircraft ice reconnaissance could be eliminated through an operational oceanographic satellite system employing radar sensors. Increasing the efficiencies of ship operations and reducing aircraft flights in the Arctic could yield savings exceeding tens of millions of dollars annually.

Weather influences all aspects of fishing operations. Wind and wave conditions affect vessel safety, the ability to deploy and secure gear, travel time from the fishing grounds to processing plants, the ability to avoid hull and gear damage, and so on. Vessels operating in the Alaskan crab fishery can experience income losses as high as $60,000 a day if operations are suspended as the result of adverse weather. All fall and winter fishing operations in the Bering Sea and Gulf of Alaska regions lose vessels and crew because of ice conditions (Figure 6). Gear losses as the result of unanticipated ice pack movements in the Bering Sea run into the hundreds of thousands of dollars annually. Seasat data analysis shows that we can expect improved forecasts of these conditions through satellite observations of wind- and surface-temperature phenomena.

Some fish species (such as tuna and salmon) exhibit strong preference for certain temperature ranges. More than 90 percent of the total catch of certain species and all successful fishing operations are conducted within certain temperature bands. Upwelling brings nutrients to the surface and attracts marine life. Convergence along a line can concentrate nutrients and cause a noticeable color boundary. Currents produce convergence and/or divergence when they interact with the coast, the seabed, or other currents. Any of these processes may contribute to the presence or absence of fish concentrations at a particular time. Satellite-derived observations of ocean surface color, sea-surface temperature, surface wind shear, and current slopes all have specific application and benefit to commercial fishing operations. Such information would improve overall efficiency and safety. Fuel

Figure 3. Drillship in Arctic operations. (Photo courtesy of Canadian Marine Drilling, Ltd.)

costs could be reduced, gear losses could be minimized, catch statistics could be improved, and insurance rates could be lowered.

The Satellite Data Distribution System

For commercial operators conducting marine activities, weather data is a highly perishable commodity. To be valuable, marine weather data must be processed and made available to the user in near real time. Observations, either conventional (ship reports) or satellite-derived, that are much older than eight hours are of little value except for climate studies or model developments.

As an outgrowth of the Seasat program, a data processing and distribution system has evolved that is capable of processing satellite-derived ocean observations, generating ocean analysis and weather forecasts, and distributing (on a near-real-time basis) these products to a limited set of commercial users. This system (Figure 7), known as the Satellite Data Distribution System (SDDS), is based on the system used by the U.S. Navy Fleet Numerical Oceanography Center (FNOC). It serves

Figure 4. Drilling operations from an artificial island during winter. (Photo courtesy of Canadian Marine Drilling, Ltd.)

Figure 5. Remote sensing of the surface roughness of sea ice is important to frontier operations. (Photo courtesy of Canadian Marine Drilling, Ltd.)

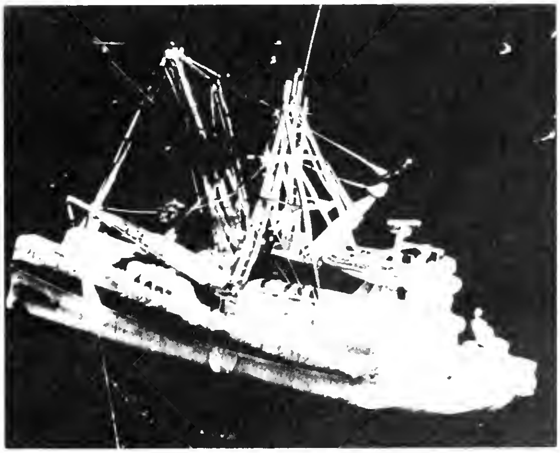


Figure 6. Vessel and crew loss resulting from severe ice conditions. (Photo courtesy of Kodiak Marine Surveyors)

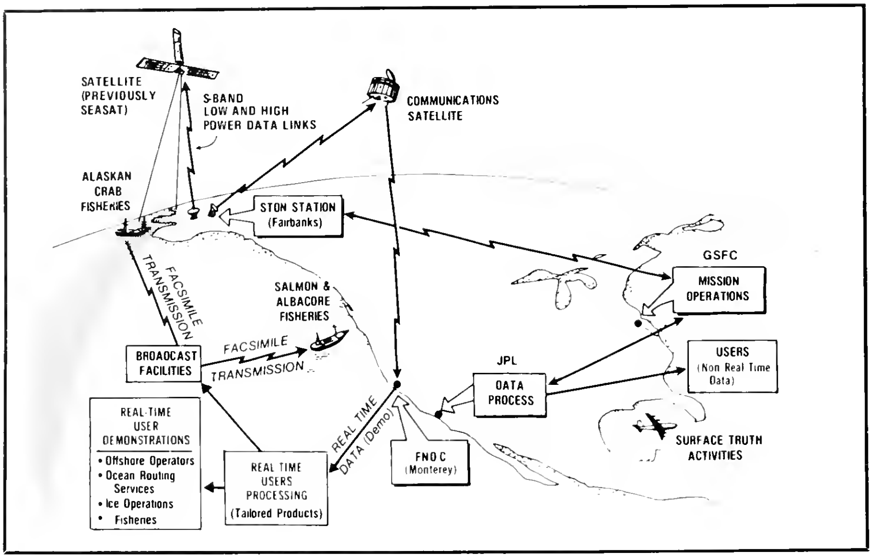


Figure 7. A satellite data distribution system provides satellite-derived ocean observations and forecast products to commercial users.

as a pilot demonstration from which the general system requirements are developed for future operational ocean-oriented satellite programs, and provides support for limited real-time experiments that test the utility of satellite observations in various maritime applications. The products available from the SDDS represent the state-of-the-art in global oceanic weather analysis and forecasts. They include: sea-level and upper atmospheric pressure, sea-surface temperature, marine winds, significant wave heights, spectral wave data, along with files of conventional observations. The sea-surface temperature (SST) observations from the Scanning Multichannel Microwave Radiometer (SMMR) on NASA's Nimbus-7 satellite, and SST analysis products incorporating these Nimbus-7 observations, will be available to commercial users from the SDDS this year.

The SDDS provides data to users on demand. Although the user can obtain products either in a teletype format or on a computer-to-computer basis, most obtain charts on CRT displays and companion hard-copy units (Figure 8). Radio-facsimile broadcasts of graphic weather charts provide on-board SDDS information for operating vessels, thus making possible the use of satellite-augmented ocean-condition forecast charts as a tactical decision-making tool for ships at sea.

A Fisheries Demonstration

Investigators are still learning how satellite observations of the ocean can be useful and beneficial to commercial operations. It is possible to assess the usefulness of various satellite-borne sensors in private-sector applications, and, with the aid of well-crafted government/private-sector partnerships, efficiently transfer the satellite technology from government-sponsored research to private-sector support and refinement for long-term industrial use and benefit.

An investigation is under way to test the applicability of selected satellite observations to U.S. west coast commercial fishing operations. Ocean color boundaries derived from the Nimbus-7 Coastal Zone Color Scanner (CZCS) along with SMMR sea-surface temperature measurements, also from Nimbus-7, are being merged with conventional and other satellite observations to form charts depicting key environmental properties that may contribute to more efficient and safe commercial fishing operations (Figure 9). These charts are made available to commercial fishing vessels through daily radio-facsimile broadcasts (Figure 10). Overall, the investigation proceeds in an experimental fashion but within the context of an operational setting, thus providing a valid basis for evaluating the commercial utility of the satellite observations.

Figure 11 shows a chart that depicts key color boundaries as derived from CZCS observations of the ocean surface in cloud-free areas. Color boundaries may identify nutrient-rich regions in which fish may congregate. Figure 12 is a chart depicting a number of ocean surface properties, including key isotherms that define the boundaries of surface temperatures preferred by albacore; coastal surface temperature of importance to trawl fisheries; wind and wave parameters; and areas of wind convergences indicative of both squall activity and possible concentrations of nutrients.

This investigation, proceeding over a three-year period, involves a continuing evaluation by participating commercial fishermen. The results

Figure 8. Satellite Data Distribution System (SDDS) user terminal configuration.

Figure 10. Radio-facsimile installations permit commercial fishing vessels to receive improved marine weather forecasts in chart form.

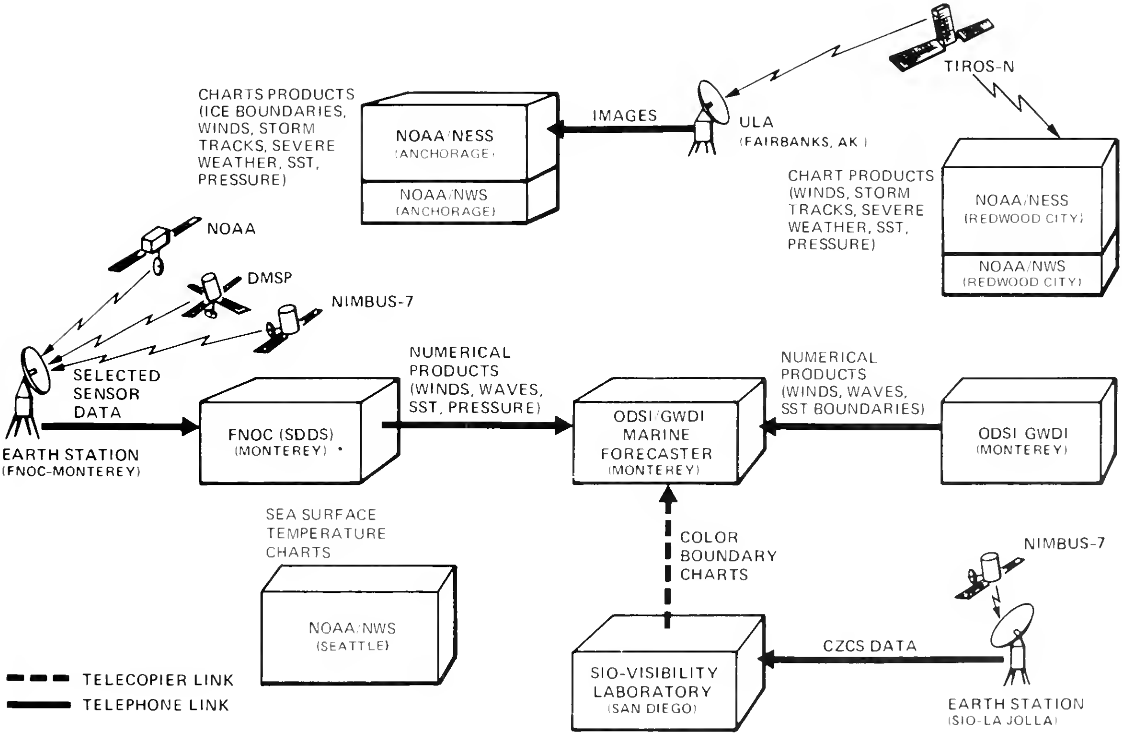


Figure 9. Data sources and routing for an experimental fisheries evaluation of satellite observations of the ocean.

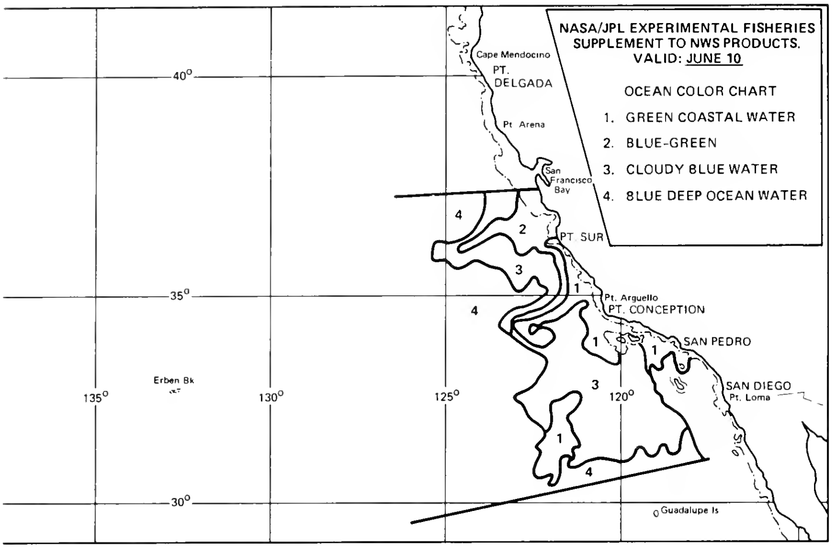


Figure 11. A special satellite-derived ocean color chart tailored for commercial fishing applications.

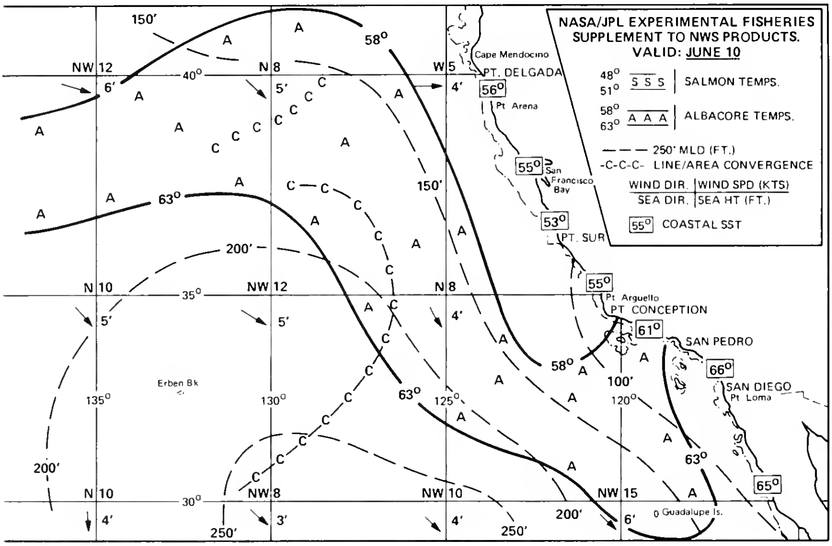


Figure 12. A special fisheries-aid chart depicting several satellite-derived ocean properties of potential use in commercial fishing applications.

of the investigation will affect whether the use of satellite observations and derived products will be continued fully funded by the participating fishermen, or discontinued because of lack of experimental success and interest.

In the Future

In the next decade, the oceans' commercial users will require an operational oceanographic satellite system or systems capable of maximizing real-time data coverage over all ocean areas; Seasat studies indicate that three spacecraft are required to achieve this. The sensor suite should measure surface winds, wave heights (and spectral energy distribution), ice characteristics, sea-surface temperature, ocean colorimetry, height of the geoid, salinity, and subsurface thermal structure. It is essential that oceanographic data be distributed to commercial users within two hours of observation time. It also is necessary for a responsive oceanographic satellite data archive to become a reality.

An estimate of the potential dollar benefits of such an operational oceanographic satellite system is summarized in Table 2.

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Table 2. Estimated impact of remote ocean sensing on commercial operations.

Measurement	Primary Beneficiaries	Application	Estimated Annual Benefits ($M)
Ocean surface winds	National environmental centers	Short-range prediction	500-1,000[a]
	Shipping	Ship routine/scheduling	20-30
	Deep-ocean mining	Operations/scheduling	2-5
	Offshore oil and gas	Operations/scheduling	25-50
	Commercial fishing	Tactics/scheduling	4-10
Waves	Shipping	Ship routing	20-50
	Offshore oil and gas	Operations/scheduling	75-150
	Marine construction	Design/construction	10-20
	Deep-ocean mining	Operations[b]/scheduling	5-10
	Commercial fishing	Tactics/safety/scheduling	2-5
Sea-surface temperature	Climate research	Monitoring/prediction	na
	Commercial fishing	Tactics/area selection	3-5
Sea ice	Arctic oil and gas	Operations/scheduling	40-60
	Ice patrol	Aircraft replacement	10-20
Colorimetry and salinity[c]	Commercial fishing	Tactics/area selection	10-20
Subsurface thermal structure[d]	Commercial fishing	Tactics/depth selection	na
Total annual benefits			$736-1,445 M
Total annual benefits (ocean commercial only)			236-445 M

[a] Includes benefits to agriculture and other nonocean operations.
[b] Includes dynamic station keeping.
[c] Salinity represents new sensor technology.
[d] New sensor technology; greatest benefit to military acoustics.

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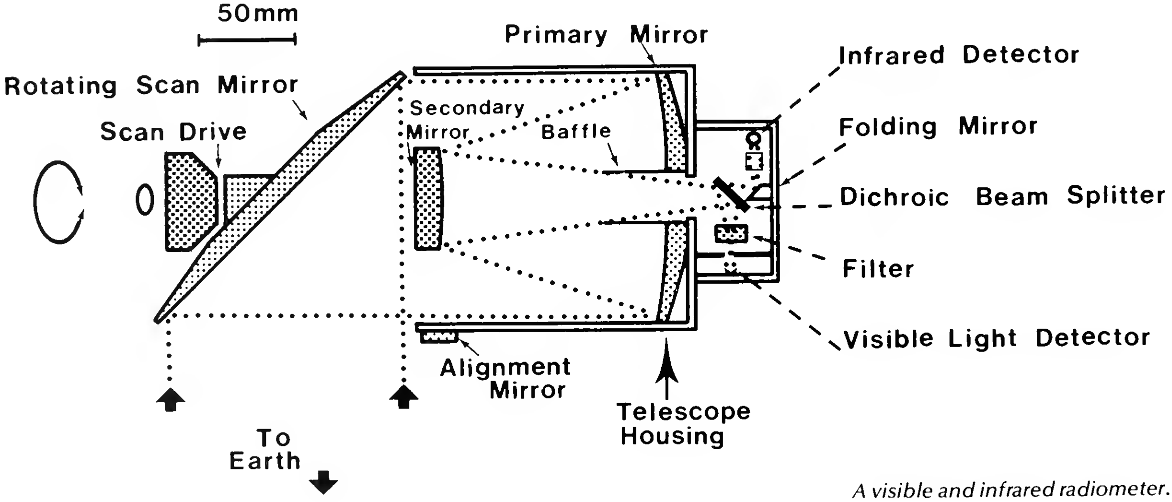
Satellite Oceanography :

THE INSTRUMENTS

by Robert H. Stewart

Instruments that observe from space have been largely developed outside the oceanographic community. Radio astronomers, studying extraterrestrial phenomena, first needed to understand the propagation of electromagnetic radiation through the atmosphere. Planetologists — scattering radio waves from the moon, Mars, Venus, and Mercury (using transmitters on earth and on interplanetary spacecraft) — demonstrated practical ways in which radiation can probe rough surfaces. Radio scientists, studying the propagation of radio signals, often examined the phenomena that influenced the propagation, thus converting propagation effects into oceanographic signals. Meteorologists, analyzing the infrared signals observed by their satellites, showed they could map the thermal features at the sea surface. All noticed the varied ways in which electromagnetic radiation interacts with matter, and all exploited this interaction to their benefit. In some cases, the general properties of scatter and emission from rough surfaces were studied. Thus a surprising number of ways that the sea surface might be observed were catalogued. In other cases, studies led to the design and construction of specific oceanographic instruments — able to measure surface winds, waves, temperature, currents, salinity, internal waves, sea ice, and bathymetry (with varying degrees of accuracy and precision).

The rapid development of instruments and techniques was the result of a number of influences, and paramount among them was the design and launch of several new satellites for observing the sea. These included Geos-3, Seasat, and Nimbus-7, as well as new techniques for extracting oceanographic information from sensors on other satellites. For example, infrared observations made by meteorological satellites can now be processed, showing thermal patterns at the sea surface. The application of these data to the



A visible and infrared radiometer.

study of oceanographic problems has progressed so that a wide variety of instruments are now being used to observe the sea.

A few problems are common to all the instruments. First, no instrument is sensitive to only one oceanographic variable; rather, each instrument responds to a combination of atmospheric and oceanic phenomena. This complicates the interpretation of data, and usually requires that a number of observations, each sensitive to somewhat different phenomena, be combined to provide unambiguous information.

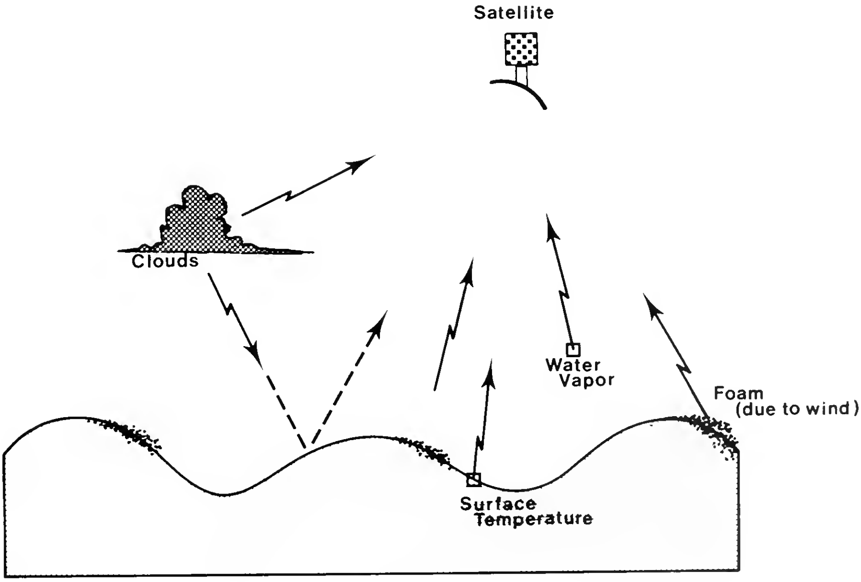
For example, infrared radiometers are designed to measure the radiant heat given off by the sea. They respond not only to sea-surface temperature, but also to clouds — low clouds being almost indistinguishable from slightly cool seawater. But clouds are white and the sea is deep blue; and a picture of the sea taken with visible light can usually be used to identify the clouds, thus allowing the radiometer to measure sea-surface temperature. Second, satellite instruments generally do not measure oceanic phenomena directly. Rather they measure some other factor, such as upwelling infrared radiation, which is only indirectly related to the variable of interest (sea-surface temperature in this example).

Both these problems compromise the usefulness of the instruments. Removing the influence of extraneous variables is difficult. Indirect measurements are not necessarily closely correlated to the primary variable. Calibration of the instrument is made more difficult because errors cannot be attributed to one particular influence. Fortunately, similar problems have often been solved by other disciplines. The application of remote sensing to oceanography can draw on these experiences.

Types of Instruments

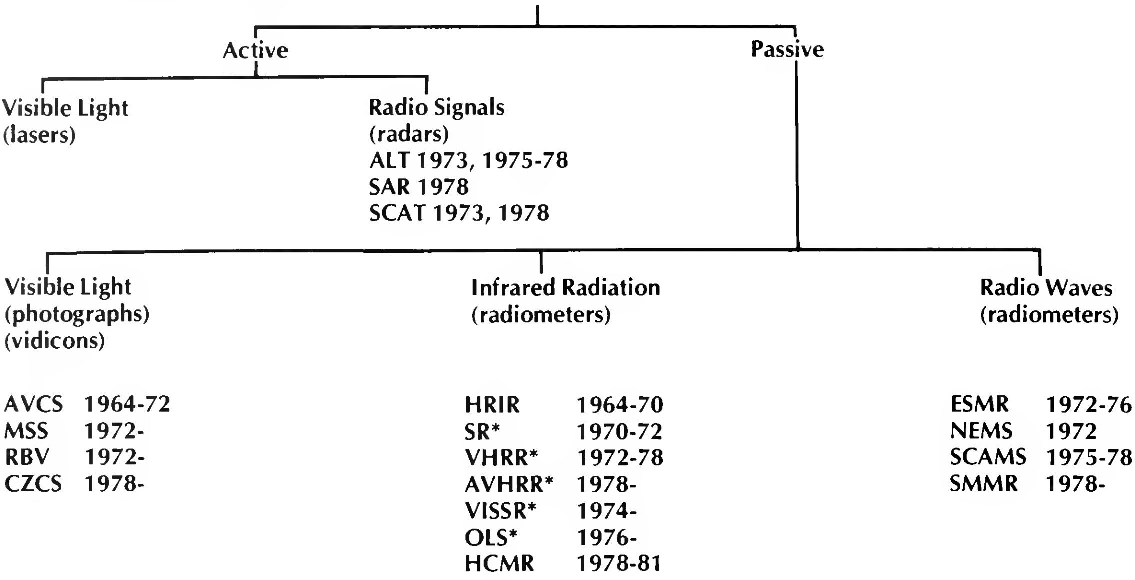
Instruments for remote observation of the ocean are of two types — passive and active. Passive instruments, such as televisions, cameras, or radiometers, observe natural radiation, using this to measure oceanic variables like surface temperature, wind speed, ocean color, and chlorophyll content. Active instruments, such as radars and lasers, send out precise signals, and then observe the signals as they are reflected back from the surface, measuring variables such as wind velocity, surface currents, and wave height (Table 1). Instruments can be further subdivided in terms of the wavelength of radiation observed: light (with wavelengths between 0.4 and 0.8 micrometers), infrared (in two bands, one with wavelengths between 3.5 and 4.0 micrometers, the other between 10 and 12 micrometers), or radio signals in the super high-frequency band (with wavelengths between 1 and 10 centimeters).

Each of the three bands of radiation has its merits. Instruments using the relatively short wavelengths of light or infrared radiation make measurements with high spatial resolution. They cannot, however, see through clouds. Radio-frequency instruments have poor spatial resolution even with antennae several meters in diameter, but they are able to see through clouds. Each band is sensitive to different phenomena, even if the instruments are measuring the same variable. For example, both infrared and radio-frequency



Infrared and radio-frequency emissions from the sea surface, from foam, and from the atmosphere allow spaceborne radiometers to measure surface temperature, winds, and atmospheric water vapor.

Table 1. Spaceborne instruments for viewing the sea.



Active

Visible Light
(lasers)

Radio Signals
(radars)
ALT 1973, 1975-78
SAR 1978
SCAT 1973, 1978

Passive

Visible Light
(photographs)
(vidicons)

AVCS 1964-72
MSS 1972-
RBV 1972-
CZCS 1978-

Infrared Radiation
(radiometers)

HRIR 1964-70
SR* 1970-72
VHRR* 1972-78
AVHRR* 1978-
VISSR* 1974-
OLS* 1976-
HCMR 1978-81

Radio Waves
(radiometers)

ESMR 1972-76
NEMS 1972
SCAMS 1975-78
SMMR 1978-

* also view with visible light
ALT = Altimeter
AVCS = Advanced Vidicon Camera Systems
AVHRR = Advanced Very High Resolution Radiometer
CZCS = Coastal Zone Color Scanner
ESMR = Electrically Scanned Microwave Radiometer
HCMR = Heat Capacity Mapping Radiometer
HRIR = High Resolution Infrared Radiometer
MSS = Multispectral Scanner
NEMS = Nimbus-E Microwave Scatterometer
OLS = Optical Line Scanner
RBV = Return Beam Vidicon
SAR = Synthetic-Aperture Radar
SCAMS = Scanning Microwave Spectrometer
SCAT = Scatterometer
SMMR = Scanning Multifrequency Microwave Radiometer
SR = Scanning Radiometer
VHRR = Very High Resolution Radiometer
VISSR = Visible and Infrared Spin Scan Radiometer

radiometers are sensitive to sea-surface temperature. However, their sensitivity to other variables differs. Thus infrared radiometers are very sensitive to clouds but not to white caps, whereas the reverse is true for radio-frequency radiometers.

Passive instruments for observing visible and infrared radiation usually have been combined; such an instrument was carried aboard the first earth-observing satellite, Tiros-1, in 1960. Tiros is an acronym for Television and Infrared Observational Satellite. The instrument, and the technique for processing its data, were crude, but it provided the first view of cloud patterns over vast areas. Progress, however, was rapid; by 1966, the High Resolution Infrared Radiometer (HRIR) on Nimbus-2 was able to observe patterns of sea-surface temperature. The most recent instrument — the Advanced Very High Resolution Radiometer (AVHRR) — is now routinely mapping sea-surface temperature with a precision of a fraction of a degree Celsius over swaths 2,700 kilometers wide with a spatial resolution of one kilometer.

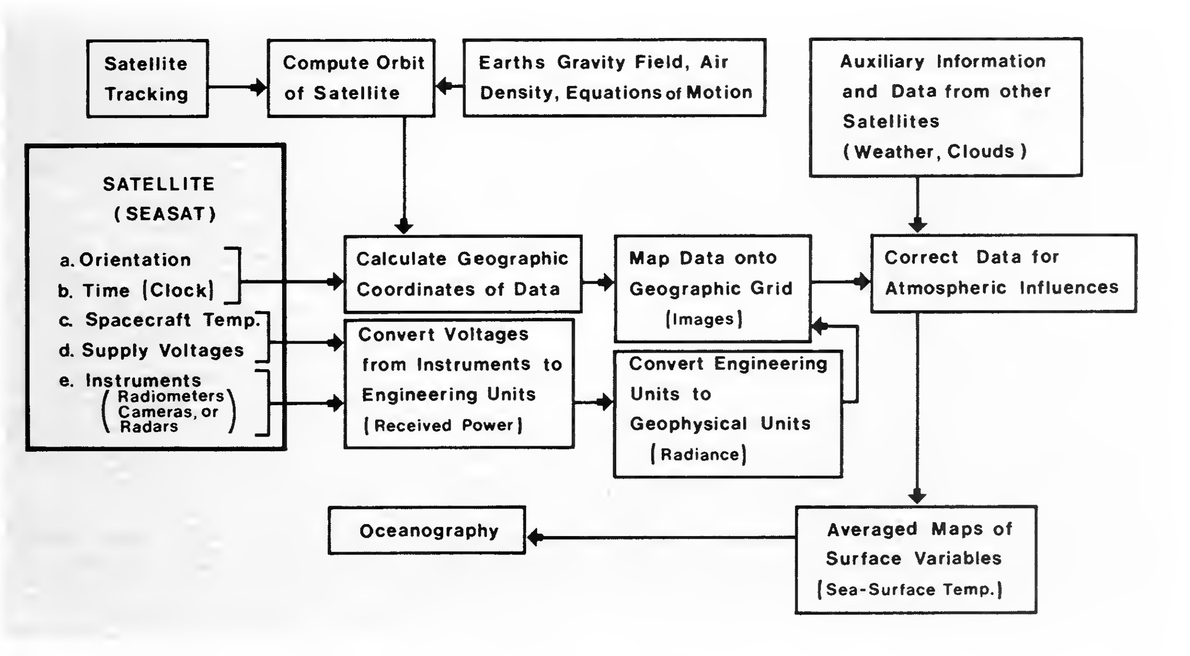
The visible and infrared instruments work much like television cameras, with only technical differences. They collect radiant energy through a lens, and focus it on a collector that converts the energy into an electronic signal. At the same time, the instrument scans back and forth across the satellite track as the satellite moves along, thus mapping the distribution of radiant energy along a swath centered on the subsatellite track.

The primary oceanographic purpose of infrared instruments (which were designed for meteorology) is to observe sea-surface temperature; and the primary source of error is clouds not seen in visible light — the influence of clearly visible clouds being easily removed. The bothersome clouds are either tenuous high cirrus, or low clouds too small to be seen by the visible light channel. In either case, they cause the instrument to read low and introduce errors of a few degrees Celsius even in the best observations. Water vapor introduces a larger discrepancy, but the effect for the most part can be removed. Because of these errors, infrared instruments are used primarily to observe patterns of temperature, rather than the actual values of the temperature.

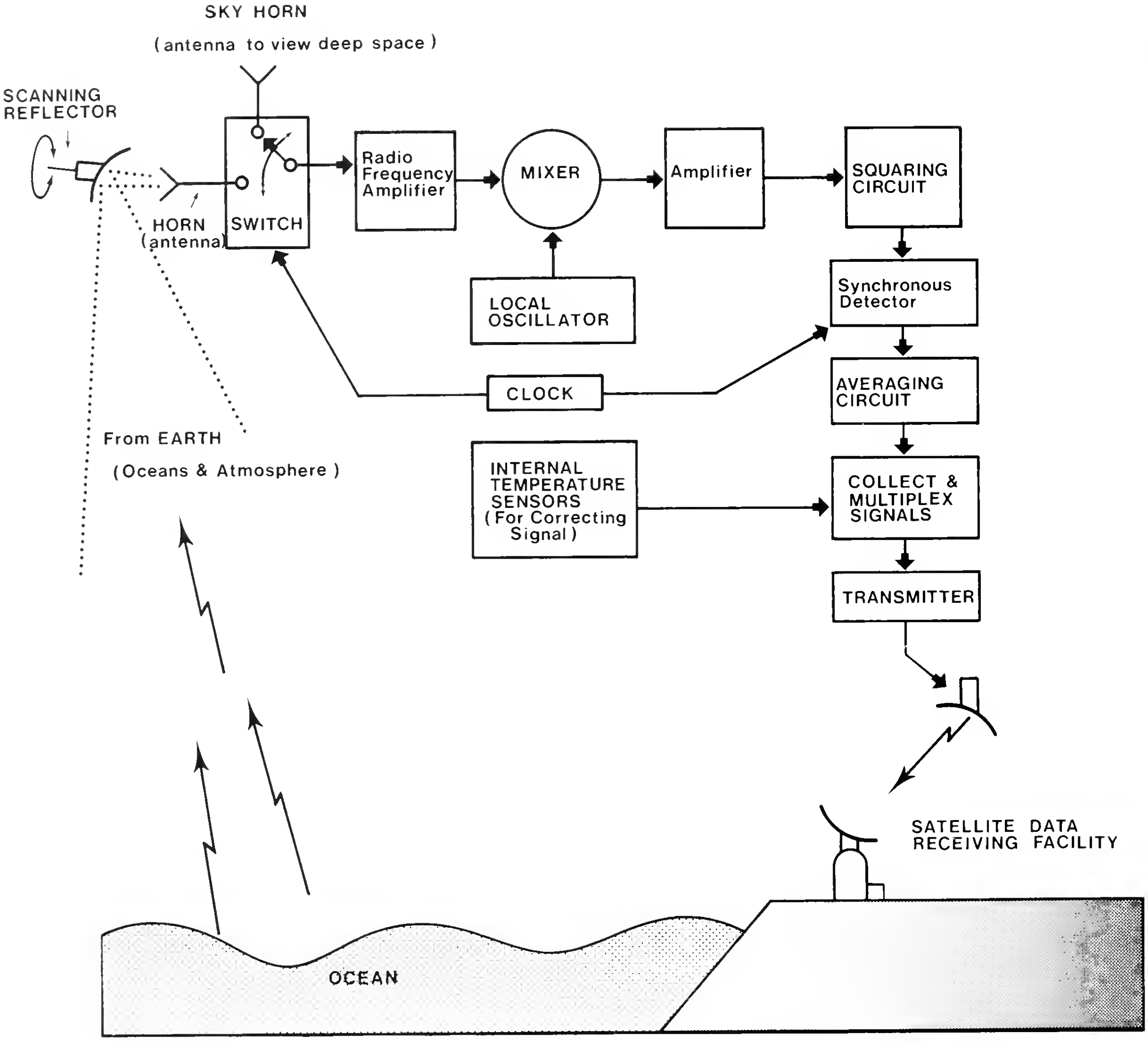
The visible-light instruments also have a long history, and are now well developed. The Multispectral Scanner (MSS) on the Landsat series of satellites produces pictures 100 kilometers across, with a resolution of 80 meters, in bands of yellow, red, and near-infrared light. Careful processing of the images shows surface and internal waves, patches of plankton, and plumes of sediment. This instrument was soon followed by the Coastal Zone Color Scanner (CZCS), an advanced television-like instrument especially designed for oceanography. Like the MSS, it observes visible light, but it is much more sensitive. By accurately mapping the subtle hues of surface color in the blue, green, yellow, red, and near-infrared light bands, it can observe chlorophyll-like pigments in the water. This instrument is used to map the distribution of plankton blooms in the water, estimate oceanic productivity, and trace the flow of sediment-laden water. As with all visible images, the primary source of error is light from the atmosphere. Only 10 percent of the radiation observed at satellite heights comes from the sea, the remainder coming from the atmosphere. Great care must be taken to remove the influence of the atmospheric signal.

Compared with the visible and infrared instruments, the radio-frequency instruments are a much more recent development. They began with radiometers, such as the Electrically Scanned Microwave Radiometer (ESMR) and the Nimbus-E Microwave Radiometer (NEMS) carried on Nimbus-5 and 6, continued with the super high-frequency radar carried on Skylab, and culminated with the four radio instruments especially designed for oceanography carried on Seasat.

Radiometers are commonly known as the radio telescopes used by astronomers. A scanning



A few of the steps necessary to convert data from satellite instruments into oceanographic information. A typical example of the information produced at some of the steps is given in parentheses.

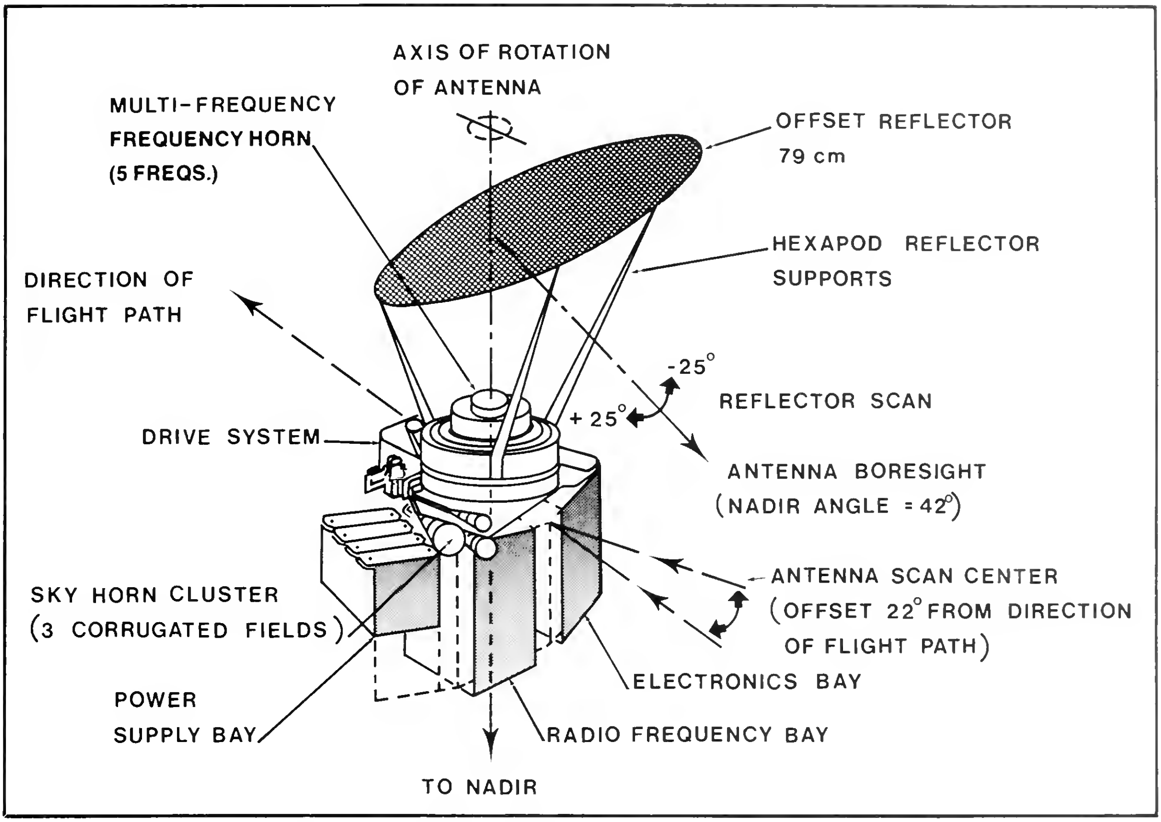


A radio-frequency radiometer. Radio-frequency emissions from the ocean and atmosphere are compared with the 3-degree (Kelvin) temperature of space, amplified, and transmitted to earth where the signals are further processed to produce maps of sea-surface temperature, wind, and atmospheric water vapor.

antenna sends signals to a very sensitive radio receiver. The instrument listens to the radio noise emitted by the atmosphere and sea surface. Because water vapor, water drops, foam, seawater, and ice all emit radiation, although at different rates in different frequency bands, radiometers must measure radiation in a number of bands in order to observe each source of radiation.

The development of radiometers for observing the sea resulted in the Scanning Multichannel Microwave Radiometer (SMMR) carried on Seasat and Nimbus-7, both launched in 1978. This instrument observes radiation in five frequency bands with a resolution of a few tenths of a degree Celsius. It produces global maps of the radiation from these bands with spatial resolution of 21 to 121 kilometers, depending on the frequency observed.

The primary source of error in the observations is the inaccuracy in the relationships between each variable of interest and the radiation in the various frequency bands. Even with these errors, the instrument appears to be able to measure sea temperature with an accuracy of 1 degree Celsius, wind speed (through observation of foam) with an accuracy of 1 to 2 meters per second,



The Scanning Multifrequency Microwave Radiometer (SMMR) carried on Seasat and Nimbus-7.

and water vapor with an accuracy similar to that of radiosonde* observations.

Radars, the last class of instruments to be flown in space, send out a pulse of radio energy and observe the characteristics of the reflection or echo from the sea surface. Two basic observations are made: 1) the time delay between transmission and reception is used to measure the height of the satellite above the sea surface; 2) the intensity of the reflection is used to measure the roughness of the surface. At incidence angles greater than 20 degrees (the angle relative to vertical), the scatter results from wavelets having wavelengths matching the radio wavelength. Because these wavelets are closely related to the wind speed, the intensity of the scatter is primarily related to surface wind velocity.

Radar altimeters (ALT) have flown on Skylab, Geos-3, and Seasat, each version being more precise than the previous. The development of this instrument led to the Seasat altimeter which could measure the height of the satellite above the sea with a precision of a few centimeters and an accuracy of around 10 centimeters. When this height is related to the position of the sea surface relative to a particular gravitational reference surface, the geoid (and this requires accurate and independent measurements of both gravity and the satellite's orbit), the measurement is used to infer surface geostrophic currents, such as the Gulf Stream and Kuroshio current systems, eddies, and rings. The altimeter also can measure wave height and wind speed. The shape of the radar pulse is distorted when reflected from surface waves, and this enables the radar to independently measure wave height with an accuracy of about 10 percent. The intensity of the reflection is related to surface roughness, which can be related to wind speed (but not direction) with an accuracy of around 2 meters per second. Note that in contrast to other instruments that map the distribution of surface

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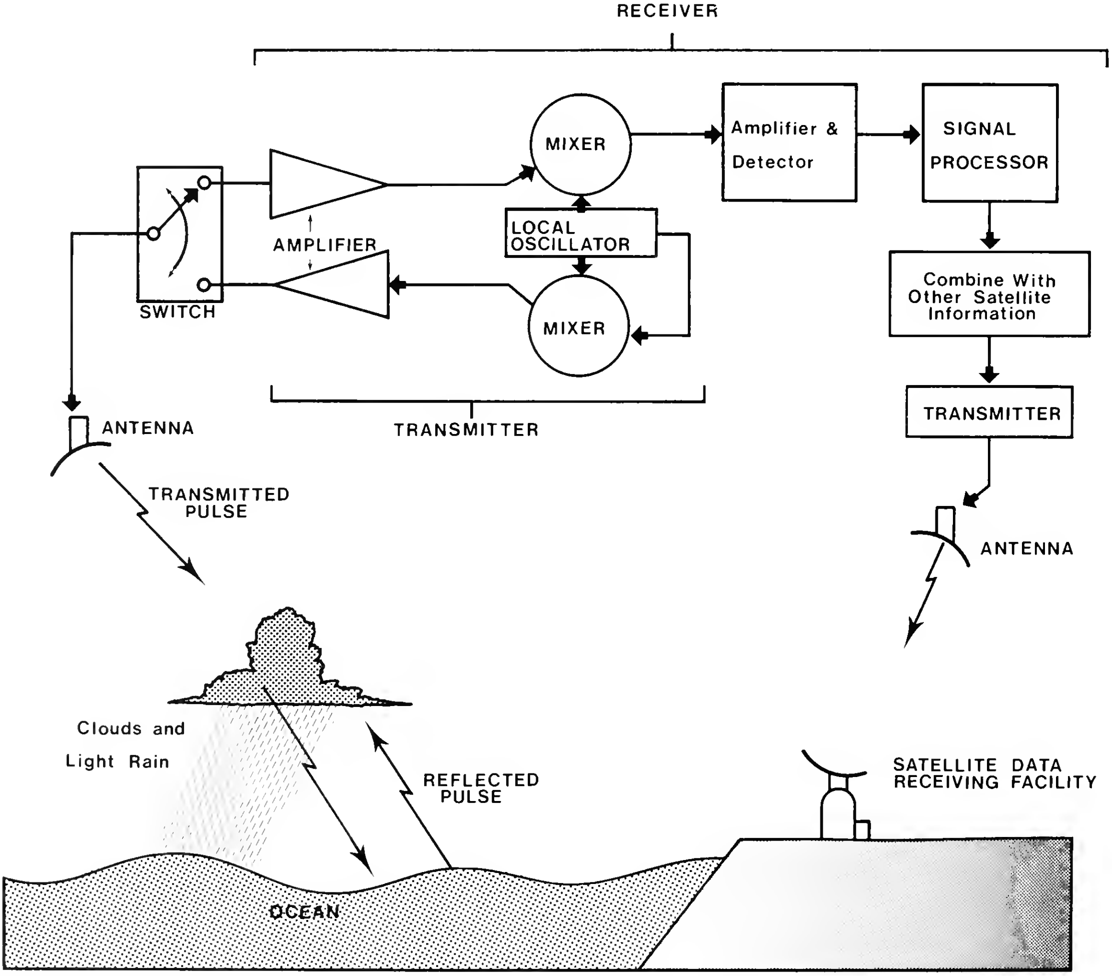
*A balloon-borne instrument for the simultaneous measurement and transmission of meteorological data using a radio frequency signal and transmitter. A pilot balloon carries the instrument aloft and a small parachute lowers it to earth when the balloon bursts in the upper atmosphere. By means of a small clockwork motor and a very lightweight radio transmitting set, signals are automatically transmitted at regular intervals during the flight to the ground. These signals give readings of pressure, temperature, and humidity at the various altitudes.

variables over wide swaths, the altimeter only views straight down, and so observes the sea along a line.

Radars designed to map the intensity of the radio-frequency scatter from the surface are called scatterometers (SCAT) and are primarily used to measure surface winds. The most recent instrument, the scatterometer on Seasat, mapped the scatter over a swath 1,500 kilometers wide with a resolution of roughly 50 kilometers. Each point on the surface was observed from two angles. The observations were combined to produce estimates of wind with an accuracy of 1 to 2 meters per second and with a twofold ambiguity on direction. The ambiguity can be removed if the general flow of the surface winds is known (for example, if the pattern is known to be the result of a storm), and when removed, data from the radar are used to map the surface wind field.

Finally, one special class of scatterometer deserves mention. The velocity of the spacecraft can be used to artificially create a very large antenna, one several kilometers long, capable of mapping the scatter with a spatial resolution of 25 meters (remember that the larger the antenna, the narrower its beam width and the better its resolution). Such a synthetic aperture radar (SAR) was flown on Seasat, and it mapped the scatter from the sea over a relatively narrow swath 100 kilometers wide. Within the swath, the variations of reflectivity tend to be subtle, caused by surface and internal waves, rain, wind gusts, tidal flow over shallow banks, and perhaps even oceanic fronts. The images from the radar rival the best Landsat images with the further advantage of being able to see through dense clouds. However, the clarity and usefulness of the image must be weighed against



Scatterometer. Transmitted radar pulses are reflected from small wavelets at the sea surface, and are used to measure ocean surface winds regardless of the presence of clouds and light rain. Radar altimeters are similar, but transmit sharper pulses toward the nadir rather than the longer pulses transmitted toward angles of 30 to 50 degrees characteristic of scatterometers.

the high cost of processing the data. The calculations used to synthesize the antenna from the data are laborious, and the data are produced at the rate of nearly ten million numbers per second.

Satellites

The satellites on which these instruments are flown are sometimes one of a kind, sometimes one of a long series, and they have a variety of orbits (Table 2). The life of the satellite, a few years at best, limits the duration of oceanographic data; and the orbit sets geographic limits on the observations.

The names of the satellites are often confusing, but tend to follow a few simple rules. The name is usually an acronym for a term that roughly describes the satellite's function, such as Erts for Earth Resources Technology Satellite. Before launch, the name is appended with a letter denoting the satellite's position in a series of similar satellites (Erts-A). After a successful launch, the letter is changed to the corresponding number (Erts-1). Occasionally, the original name is cumbersome and it is replaced by one more catchy or descriptive (for example, the name for Erts was changed to Landsat).

Satellites are either experimental, such as the Nimbus series flown by the National Aeronautics and Space Administration (NASA), or operational, flown either by the National Oceanic and Atmospheric Administration (NOAA), which operates the NOAA and Goes series of weather satellites, or by the Department of Defense, which operates the Defense Meteorological Satellite Program (DMSP). Each experimental satellite is one of a kind, even if it is one of a series of experimental satellites, and each is flown to develop instruments or techniques (Table 3). The mature instruments are flown on a particular series of operational satellites. Each satellite within a series is identical to the others, and this allows large data sets to be accumulated from them.

The coverage available from a satellite depends on its orbit. Satellite orbits are roughly elliptical, and the subsatellite track traces out a pattern with north-south limits equal to the inclination of the orbit. Polar-orbiting satellites have inclinations near 90 degrees and observe from the equator to the poles. Conversely, satellites in an equatorial orbit, such as the geosynchronous ones, always remain over the equator, although they may carry instruments that can look out as far as 60 degrees latitude.

Table 2. Satellites carrying ocean-observing instruments.

Experimental

Nimbus-1	**1964**	**AVCS**	**HRIR**		
-2	**1966**	**AVCS**	**HRIR**		
-3	**1969**	**HRIR**			
-5	**1972**	**ESMR**	**NEMS**		
-6	**1975**	**ESMR**			
-7	**1978**	**CZCS**	**SMMR**		
Skylab	**1972**	**ALT**	**SCAT**		
Landsat-1	**1972**	**MSS**	**RBV**		
-2	**1975**	**MSS**	**RBV**		
-3	**1978**	**MSS**	**RBV**		
GEOS-3	**1975**	**ALT**			
HCMM-1	**1978**	**HCMR**			
Seasat-1	**1978**	**ALT**	**SAR**	**SCAT**	**SMMR**

Operational

ITOS-1, NOAA-1	**1970**	**AVCS SR**
NOAA-2, 3, 4, 5	**1972-76**	**VHRR SR**
TIROS-14 (TIROS-N)	**1978**	**AVHRR**
NOAA-6	**1979**	**AVHRR**
SMS-1, 2		
GOES 1, 2, 3	**1974-78**	**VISSR**
DMSP		
(F1,F2,F3)	**1976-78**	**OLS**

DMSP = Defense Meteorological Satellite Program
GEOS = Geodetic Earth-Orbiting Satellite
GOES = Geostationary Observational Environmental Satellite
HCMM = Heat Capacity Mapping Mission
ITOS = Improved TIROS Operational Satellite
SMS = Synchronous Meteorological Satellite
TIROS = Television and Infrared Observational Satellite

Table 3. Instrument performance.

Instrument	Spacecraft	Geophysical Observable	Best Estimate of Measurement Accuracy	Remarks
Altimeter (ALT)	Seasat	Surface topography	± 7 cm rms *(precision)	20-30 cm absolute accuracy with laser tracking of spacecraft
		Significant wave height	±5% or 0.5 m	
Scatterometer (SCAT)	Seasat	Wind velocity	±1.6 m/s rms, speed ±16 deg. rms, direction	5-24 m/s range; directional ambiguity
Synthetic-Aperture Radar (SAR)	Seasat	Surface waves	±3% wavelength ±2 deg. direction (precision)	50-1,000 m range; rough estimate of height
		Sea ice boundaries	±250 m absolute positioning accuracy	
Color Scanner (CZCS)	Nimbus-7	Chlorophyll concentration	±30%	No clouds; low suspended sediment concentration
		Diffuse attenuation coefficient	±15%	Same as above
Microwave Radiometer (SMMR)	Seasat Nimbus-7	Surface temperature	±1 deg. C	No rain, heavy clouds, sunglint, or RFI**: 600 km or more from land
		Wind speed	±2.5 m/s, no direction	Same as above 0-2 m/s
		Fractional ice cover	±15%	
		Ice age	New or multi-year	
Infrared Radiometer (VHRR)	NOAA-6	Surface temperature	0.6 deg. C	No clouds

*root mean square

**radio frequency interference

The height of the satellite determines its period. Those with heights near 1,000 kilometers have periods of around 115 minutes, and most are in this class. The Landsats, the NOAA series of weather satellites, and the Nimbus, Geos, and Seasat experimental satellites are typical examples of this type. Those at a height of 35,900 kilometers have a period of exactly 24 hours, and are said to be geosynchronous because they remain in a fixed position relative to the earth. The Goes weather satellites, which provide pictures for television news, and communication satellites are two well-known examples of this type. Finally, the combination of height and inclination determine the rate at which the orbital plane rotates relative to the stars. Satellites with heights near 1,000 kilometers and inclinations near 100 degrees (80 degrees retrograde) have a plane that rotates 365 degrees per year, and pass overhead at the same local time each day. Such orbits are said to be sun synchronous.

The careful selection of the satellite's orbit allows the satellite to sample over areas and at times that are most useful. Wide coverage, repeated coverage every day or every few days, avoidance of sun glint, or fixed position relative to earth are all useful attributes for one or another type of observation, but, of course, all cannot be satisfied at once.

Robert H. Stewart is an Associate Adjunct Professor at the Scripps Institution of Oceanography in California and also a Research Scientist at the Jet Propulsion Laboratory of the California Institute of Technology.

Acknowledgment
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Suggested Readings

IEEE Journal of Oceanic Engineering. 1980. Volume OE-5, a special issue on the Seasat-1 sensors.

McClain, E. Paul. 1980. Environmental satellites. In *McGraw-Hill Encyclopedia of Environmental Science*. New York: McGraw-Hill.

Glossary

Albedo — is the ratio of the radiation reflected from the earth to the total amount incident upon it.

Algorithm — a detailed computational procedure that converts instrument readings (data) into geophysical measurements.

Altimetry — the technique of using radio frequency emissions (radar) to measure the altitude of a spacecraft relative to the earth's surface.

Areal percentage — a part of a whole horizontal surface area expressed in hundredths.

Azimuthal resolution — the smallest length distinguishable by an instrument in the direction normal to the trajectory of the spacecraft.

Coriolis force — a fictitious force arising from the rotation of the earth and acting at right angles to large-scale geostrophic currents.

Dendritic interface — an interface consisting of a large number of spikes or plates of solid material that project into the meld (contrasted with a planar interface).

Dielectric — a material having low electrical conductivity in comparison to that of a metal.

Footprint — the surface area of the earth that is measured at any instant by an instrument.

Geoid — a geopotential surface that coincides with the mean level of the oceans on a nonrotating earth.

Geostrophic (current) — a large-scale current in which the Coriolis force is balanced by the pressure gradient force.

Geosynchronous — an orbital characteristic of an artificial satellite in which the nadir point remains geographically fixed through time.

Ice leads — a navigable passage through floating ice (in a general way, one can jump over cracks, but not over leads).

Infrared (radiation) — that portion of the electromagnetic spectrum between the limiting wavelengths of 0.7 and 1,000 micrometers.

Lossy sea ice — a material that effectively absorbs energy (i.e., results in losses of energy).

Map correct — a map-correct display is one in which everything is appropriately scaled geometrically in a horizontal plane.

Nadir — a point on the earth's surface vertically downward and directly below the spacecraft.

Pixel — the smallest resolvable element of an image.

Radiation budget — the balance between incoming solar energy and the reflection and absorption of that energy by the earth.

Radiosonde — a balloon-borne instrument for the simultaneous measurement and transmission of meteorological (atmospheric pressure, temperature, and humidity) data.

Resolution — the ability of an instrument to form distinguishable images of objects separated by small angular distances; the smallest length distinguishable by an instrument.

Retrograde — an orbital characteristic of an artificial satellite in which the motion is in a direction opposite to that of the earth's rotation.

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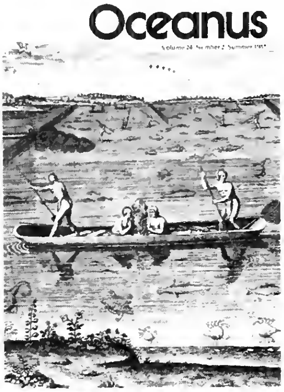

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General Issue, Vol. 24:2, Summer 1981—A wide variety of subjects is presented here, including the U.S. oceanographic experience in China, ventilation of aquatic plants, seabirds at sea, the origin of petroleum, the Panamanian sea-level canal, oil and gas exploration in the Gulf of Mexico, and the links between oceanography and prehistoric archaeology.

The Oceans as Waste Space?, Vol. 24:1, Spring 1981 — Whether we should use the oceans as a receptacle for waste or not is a question of much concern today. Topics in this issue include radioactive waste and sewage sludge disposal policies, problems of measuring pollutant effects, ocean outfalls, and mercury poisoning, as well as arguments for and against using the oceans for disposal of waste materials.

The Coast, Vol. 23:4, Winter 1980/81—Celebrating the Year of the Coast, this issue is dedicated to the more than 80,000 miles of our nation's shorelines. Included are articles on barrier islands (federal policies and hazard mapping), storms and shoreline hazards, off-road vehicles on Cape Cod, the Apalachicola experiment, and coastal resource conservation and management.

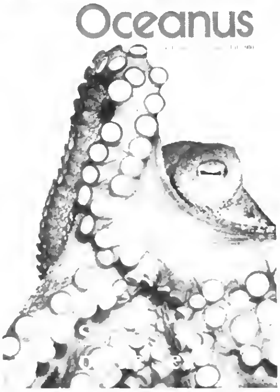
Senses of the Sea, Vol. 23:3, Fall 1980—Marine animals have complex sensory systems. Here we learn that lobsters can taste and smell, bacteria can sense their world magnetically, and some fish can sense electrically. We discover that octopuses have a sophisticated sense of equilibrium, and that some insects use the water surface to communicate. Underwater vision, hearing, and echolocation are also discussed.

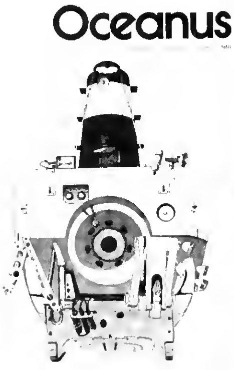
General Issue, Vol. 23:2, Summer 1980—A collection of articles on a range of topics, including: the dynamics of plankton distribution; submarine hydrothermal ore deposits; legal issues involved in drilling for oil on Georges Bank; and the study of hair-like cilia in marine organisms.

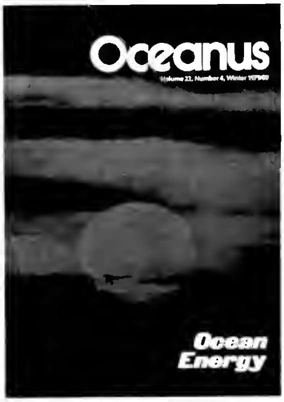
A Decade of Big Ocean Science, Vol. 23:1, Spring 1980—As it has in other major branches of research, big science has become a powerful force in oceanography. The International Decade of Ocean Exploration is the case study. Eight articles examine scientific advances, management problems, political negotiations, and the attitudes of oceanographers toward the team approach.

Ocean Energy, Vol. 22:4, Winter 1979/80—How much new energy can the oceans supply as conventional resources diminish? The authors in this issue say a great deal, but that most options—thermal and salinity gradients, currents, wind, waves, biomass, and tides—are long-term prospects with important social ramifications.

Ocean/Continent Boundaries, Vol. 22:3, Fall 1979—Continental margins are no longer being studied for plate tectonics data alone, but are being analyzed in terms of oil and gas prospects. Articles deal with present hydrocarbon assessments, ancient sea-level changes that bear on petroleum formations, and a close-up of the geology of the North Atlantic, a current frontier of hydrocarbon exploration. Other topics include ophiolites, subduction zones, earthquakes, and the formation of a new ocean, the Red Sea.







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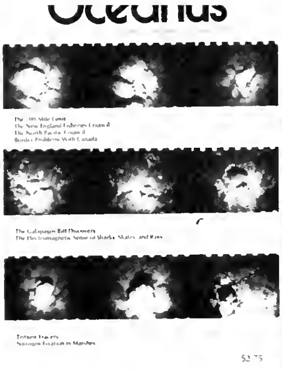

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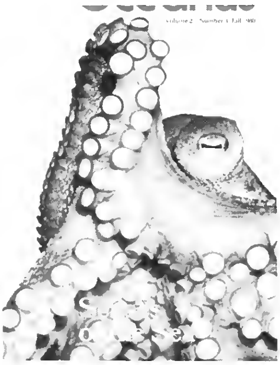

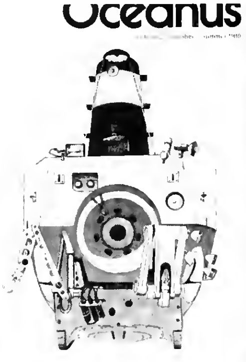

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General Issue, Vol. 22:2, Summer 1979 — *Limited supply only.*
Harvesting the Sea, Vol. 22:1, Spring 1979 — *Limited supply only.*

Oceans and Climate, Vol. 21:4, Fall 1978—This issue examines how the oceans interact with the atmosphere to affect our climate. Articles deal with the numerous problems involved in climate research, the El Niño phenomenon, past ice ages, how the ocean heat balance is determined, and the roles of carbon dioxide, ocean temperatures, and sea ice.

General Issue, Vol. 21:3, Summer 1978—The lead article looks at the future of deep-ocean drilling, which is at a critical juncture in its development. Another piece—heavily illustrated with sharp, clear micrographs—describes the role of the scanning electron microscope in marine science. Rounding out the issue are articles on helium isotopes, seagrasses, red tide and paralytic shellfish poisoning, and the green sea turtle of the Cayman Islands.

Marine Mammals, Vol. 21:2, Spring 1978—Attitudes toward marine mammals are changing worldwide. This phenomenon is appraised in the issue along with articles on the bowhead whale, the sea otter's interaction with man, behavioral aspects of the tuna/porpoise problem, strandings, a radio tag for big whales, and strategies for protecting habitats.

The Deep Sea, Vol. 21:1, Winter 1978—Over the last decade, scientists have become increasingly interested in the deep waters and sediments of the abyss. Articles in this issue discuss manganese nodules, the rain of particles from surface waters, sediment transport, population dynamics, mixing of sediments by organisms, deep-sea microbiology—and the possible threat to freedom of this kind of research posed by international negotiations.

General Issue, Vol. 20:3, Summer 1977—The controversial 200-mile limit constitutes a mini-theme in this issue, including its effect on U.S. fisheries, management plans within regional councils, and the complex boundary disputes between the U.S. and Canada. Other articles deal with the electric and magnetic sense of sharks, the effects of tritium on ocean dynamics, nitrogen fixation in salt marshes, and the discovery during a recent Galápagos Rift expedition of marine animal colonies existing on what was thought to be a barren ocean floor.

Sound in the Sea, Vol. 20:2, Spring 1977 — Beginning with a chronicle of man's use of ocean acoustics, this issue covers the use of acoustics in navigation, probing the ocean, penetrating the bottom, studying the behavior of whales, and in marine fisheries. In addition, there is an article on the military uses of acoustics in the era of nuclear submarines.

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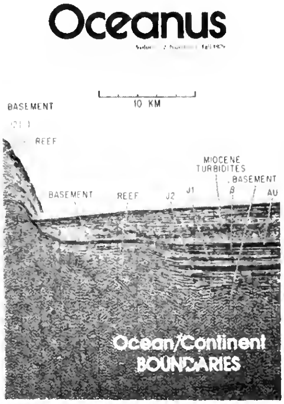

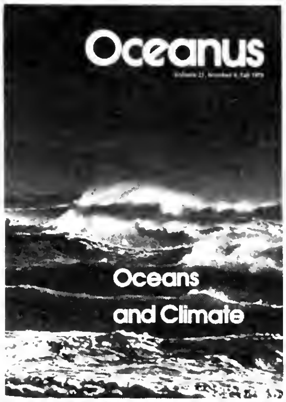

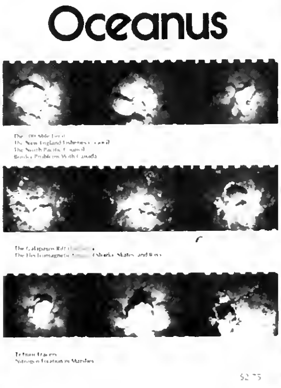

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