SPACE SCIENCE AND APPLICATIONS

Progress and Potential

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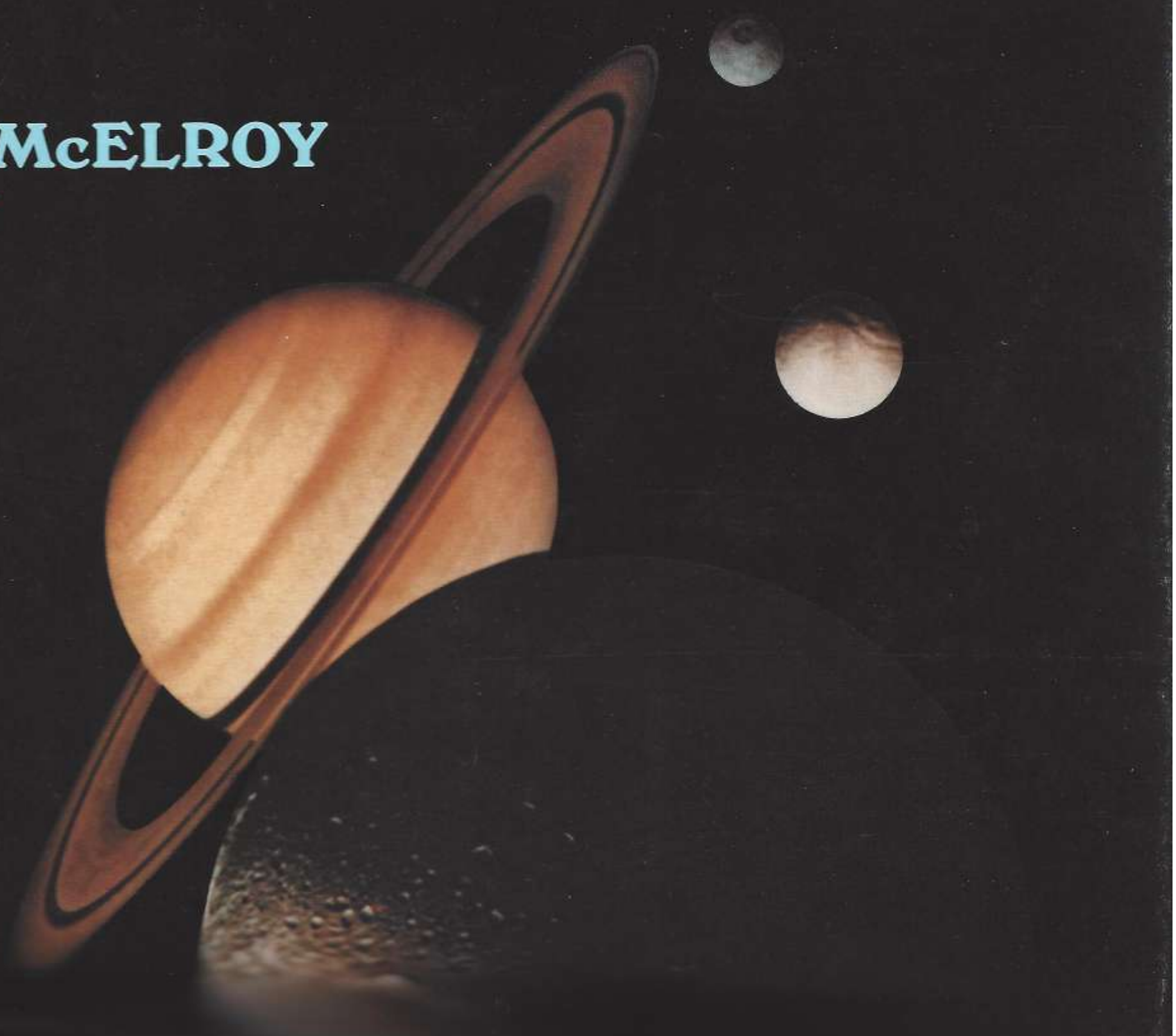
Senior Editor



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OCEAN REMOTE SENSING

Robert L. Bernstein and Payson R. Stevens

Traditional ocean measurements, from ships and moored buoys, are generally expensive to collect. Vast areas of the ocean are hardly ever observed this way. Yet the need to make global and continuous ocean measurements exists, and grows more critical with time. Remote sensing from space has been recognized for many years as the principal means by which this need may be ultimately met. During the past 15 years, NASA has developed sensor technology, and then built and launched several spacecraft dedicated in whole or in part to ocean measurements. The Seasat satellite, devoted entirely to oceanography, carried four new microwave-based sensors, during its brief three month operating life in 1978. Other satellites, with primarily geodetic and meteorological missions, have also contributed greatly to advancing the state of the art in ocean remote sensing. In this chapter, we review the areas where remote sensing has demonstrated its potential, and describe how the entire field is now poised to move from the initial demonstration phase, which is now ending, to the more mature phase of routine utilization, such as now characterizes other fields.

APPLICATION AREAS FOR OCEAN REMOTE SENSING

The needs for ocean remote sensing data are very broad. From a scientific point, the ocean interacts with the atmosphere, with the land, and with the ice-covered regions. These interactions are complex, often global in scale, and constantly changing, and require spacecraft for adequate measurement coverage. Increasing polar region mineral exploration and transportation operations require remote sensing for both safety and economy. Fisheries applications of remote sensing include the careful management of what is ultimately a limited but renewable resource. Safe and efficient ocean transportation requires accurate forecasts of wind, wave, and strong current. Naturally occurring and man-made substances introduced into populated coastal regions can be observed in detail from space, and need to be monitored more carefully. It may even prove possible to assist in marine geophysical exploration for offshore oil, gas, and minerals through some remote sensing techniques. Each of these application areas will be described in more detail, with emphasis on their remote sensing aspects.

The Ocean's Role in Weather and Climate

The ocean and atmosphere interact with each other in many different ways. The ocean responds to the force imposed by the atmosphere, with waves and currents arising from the action of the wind, and with sea surface temperatures decreasing under conditions of cold dry air blowing over warmer water. But in addition, the atmosphere itself responds to changes in ocean conditions. The ocean is able to store far more heat than the atmosphere, and retain it for a much longer time, as a result of the great differences in heat capacity and density between air and water. The upper few meters of water in the ocean can hold and release as much heat as the entire atmosphere above it. Ocean currents can then transport heat absorbed in the tropics to the higher latitudes where it may be released. In this way the gradient of temperature between the equator and the poles is moderated considerably. Fluctuations in ocean currents and temperatures, which are linked to fluctuations in atmospheric conditions, thus play an important role in producing variations in the earth's climate.

A long-term goal of oceanographers and meteorologists is to construct computer numerical models of the coupled ocean–atmosphere system, and supply these models with observations of both fluids on a global basis to make more accurate forecasts of weather and ocean conditions. Satellite remote sensing offers the promise of providing the needed observations on a frequent yet global scale.

Since a later chapter covers the remote sensing of the atmosphere and its weather, we will focus here on those aspects of remote sensing which are most important to oceanography, and the impact of the ocean on the atmosphere. For oceanography, surface wind is probably the single most important measurement which can now be made remotely from space. In 1978 the Seasat satellite carried a radar device called a scatterometer, designed to transmit microwave signals and measure the amount scattered back from small wavelets (a few centimeters in wavelength) and other roughness features of those dimensions on the ocean surface which are strongly correlated with wind. The radar backscatter measurements, which were made looking in two directions at each point on the ocean, are convertible to wind speed and direction, and agree with nearby individual ship and buoy reports. Unlike ship reports, which are concentrated on the major shipping lanes, virtually absent in the tropics and southern hemisphere, and biased away from the worst weather, scatterometry provides uniform repeatable coverage. With such an improvement in coverage, models of ocean waves and ocean currents, which are driven by surface wind, ought to provide better and more detailed results.

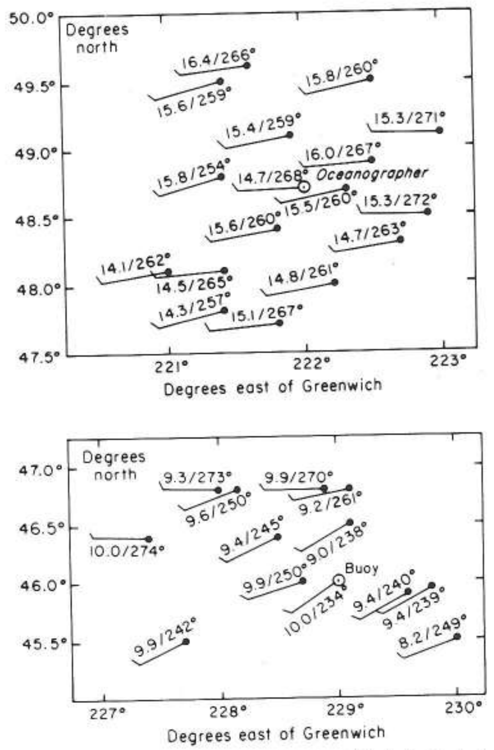


Fig. 8-1: Seasat scatterometer wind vectors (filled circles) show good agreement with North Pacific ship and buoy measurements (open circles) [7].

Solar energy absorbed in the upper ocean may be transported great distances by currents before being released back to the atmosphere. Traditional surface current measurements, from ships and buoys, are difficult and expensive to collect. Radar altimetry has attracted the attention of oceanographers for the last 15 years as a means of making this measurement from space, on a continuous global basis. The measurement principle is straightforward, but requires altimeter data of extreme precision and accuracy on the distance between an orbiting satellite and the sea surface. In the absence of any currents, tides, or other disturbances, the ocean surface would be a level, or equipotential surface of the earth's gravitational field. When a surface current is flowing, coriolis acceleration induced by the earth's rotation causes the ocean surface to tilt very slightly at right angles to the direction of flow. Thus, for example, a 1 m height difference exists across the Gulf Stream. To be useful on a global basis, altimeter measurements must be accurate to a few centimeters. Remarkably enough, it has been possible to build and demonstrate such accuracies. The Seasat radar altimeter was designed to give 10 cm accuracy, and in fact yielded data a factor of two better than that.

In order to obtain surface current information from radar altimetry, two additional pieces of data are required. First, the orbit of the satellite must be determined to comparable accuracy, and second, the earth's equipotential surface, usually referred to as the geoid, must also be known to the same accuracy. While it is not possible yet to determine orbits and the geoid to the requisite accuracies, significant progress is being made. For example, modest improvements to the tracking system used on Seasat would today provide 14 cm accuracy in the radial component of the orbit for a single overpass, and would give an even lower value through time-averaging of multiple passes. The next generation of NASA radar altimeter missions will use the global positioning system satellites, which are expected to provide orbit accuracies of a few centimeters. For the geoid determination problem, NASA has proposed GRM, the Geophysical Research Mission, which should give a dramatic improvement in knowledge of the geoid.

Yet even before such improvements in orbit and geoid are in hand, altimetry is still capable of providing valuable information on the time-fluctuating part of currents. The best data set to demonstrate this capability of altimetry was obtained during the Seasat mission. NASA's next generation altimeter mission, called TOPEX for ocean topography experiment, is expected

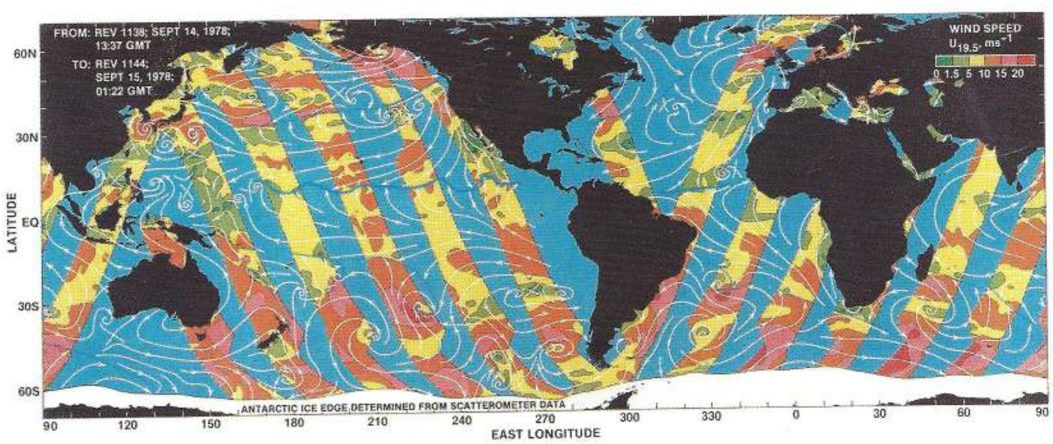


Fig. 8-2: Map of the surface wind field constructed from 12 hours of Seasat scatterometer data. Measurements of wind speed and direction are restricted to the colored swaths, where dark green denotes speeds less than 1.5 m/s, and red areas are in excess of 20 m/s; prepared by P. Woiceshyn (JPL), M. Wurtele (UCLA), S. Peteherych (AES-Canada), D.H. Boggs (dB Enterprises), and R. Atlas (NASA/GSFC).

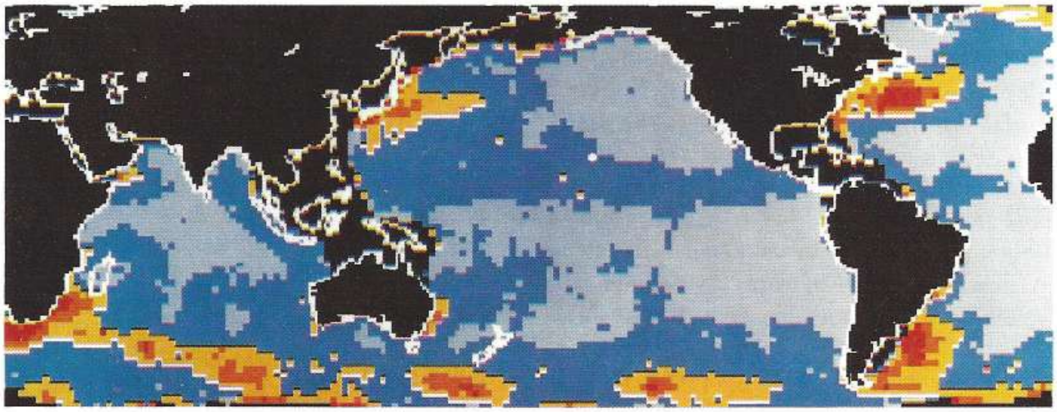


Fig. 8-3: Global map of surface height variability, showing local maxima in the Gulf Stream, Kuroshio, and Antarctic Circumpolar currents [2].

to fly in the late 1980's, and further the state of the art of radar altimetry, demonstrate that surface currents can be mapped globally on a regular basis, and provide three or more years of this data.

In addition to surface wind and surface current, the total amount of heat stored in the upper ocean is of great importance to climatological studies. This requires measurements of ocean temperature extending from the surface down to a depth of several hundred meters or more. While altimetry may possibly be used to give the vertical integral of heat storage, the vertical distribution of the storage is most important, and no remote sensing technique can provide that information. Yet the surface temperature itself can now be determined to useful accuracy, and may, in concert with altimetry and scatterometry, provide sufficient constraints on models of upper ocean processes to adequately estimate the vertical distribution of stored heat.

Sea Ice

At any one time, sea ice covers approximately 13 percent of the world's oceans, and its thickness, extent, and composition affect global climate and weather. Remote sensing permits measurements to be made in regions that may be inaccessible by any other means. Extreme cold, cloud cover, winds, dark polar winters, and constantly moving ice floes make the polar seas the most hazardous on earth. Prior to satellites, little was known about seasonal or year-to-year variations in sea ice cover. Satellite surveys also provide the practical advantage of finding shorter and safer sea routes for military and mineral exploitation operations in polar regions.

Visual and Infrared Techniques

The Landsat multispectral scanning system (MSS) and the NOAA weather satellite advanced very high resolution radiometer (AVHRR) have both been used to collect imagery in the visual and infrared portions of the spectrum. Landsat offers a higher resolution (30–80 m) than the AVHRR (1–4 km), and has proved useful for studies of ice conditions in local areas. AVHRR images have been used to monitor large-scale pack ice behavior.

Visual and thermal infrared systems rely on sensing reflected sunlight or the thermal emission from ice or snow surfaces, but cannot readily distinguish first-year from multi-year ice. Persistent cloud cover over much of the polar oceans limits coverage substantially. Instead, such imagery is primarily used for large-scale observations of sea ice movement and extent.

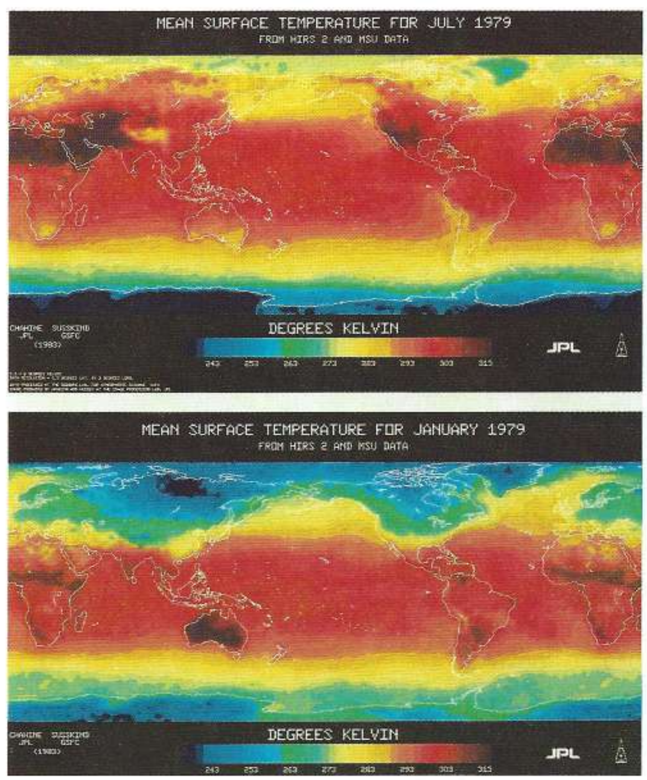


Fig. 8-4: Global surface temperature maps for July (top) and January (bottom) 1979, constructed from NOAA weather satellite infrared and microwave radiometer data; provided by J. Susskind and D. Reuter (Goddard Space Flight Center), M. Chahine and K. Hussey (JPL). For further details see [8].

Microwave Sensing Techniques

Both visible and infrared systems are severely limited by darkness and cloud cover, with consequently infrequent opportunities for imaging. Satellite microwave techniques fortunately do offer all-weather, day and night observations of the polar regions. Microwave observing systems employ either active or passive techniques. Active systems (radars) observe the energy scattered back from snow, ice, and open water surfaces. Passive systems (microwave radiometers) measure the electromagnetic energy emitted by matter. Emission properties at various microwave wavelengths differ markedly from open water, ice of various ages, and land surfaces with or without snow cover.

Passive Microwave Measurements

Two main passive microwave sensors have been used for observing sea ice. In 1972, NASA launched the electrically scanning microwave radiometer (ESMR), the first satellite sensor to provide global data on sea ice extent. ESMR provided data until 1983, covering 1400 km wide swaths with a resolution of about 25 km. It has provided large-scale mapping in the polar regions showing the percentage of ice cover from month to month and from one year to the next. Images constructed from ESMR data have provided the first clear picture of sea ice changes around Antarctica and in the Arctic Ocean.

The scanning multifrequency microwave radiometer (SMMR), another passive sensor, was launched in 1978 aboard the Nimbus 7 satellite. By observing at five different microwave frequencies, it eliminated certain ambiguities associated with the ESMR's single frequency, and has provided excellent sea ice data. SMMR has a 780 km swath with a spatial resolution between 30 and 150 km, depending on the frequency employed. SMMR has successfully provided images of sea ice concentration and the multiyear ice fraction in the Arctic Ocean. The SMMR ice data are now routinely used to guide civilian and military polar operations. In 1986 the U.S. Department of Defense polar orbiting meteorological satellites will begin carrying a microwave radiometer (termed SSM/I, for special sensor microwave/imager), which will provide ice data of even higher quality. Between ESMR, SMMR, and SSM/I, it will be possible to examine sea ice cover and its variability over decade time scales, with important implications for climate studies, and the long-term global warming hypothesized to result from the steady increase in atmospheric carbon dioxide. Modeling results predict that this warming will be most pronounced in the polar regions. Thus, the total amount of sea ice, as observed by these sensors from 1972 to 1986 and beyond, may be the first clear indication of such warming.

Active Microwave Measurements

Though passive microwave sensors provide synoptic data, their low resolution (tens of kilometers) restricts their utility to large-scale applications only. In contrast, synthetic aperture radar (SAR) is an active microwave sensor with very high resolution. An *L*-band wavelength (25 cm) SAR was flown on Seasat in 1978, and provided imagery at 25 m resolution. During its 100-day life the Seasat SAR provided detailed ice data as it covered its 100 km swaths. During the last 30 of those 100 days exactly repeating coverage was possible every three days. Radar returns give information, independent of any cloud cover, on the roughness of the surface, thus identifying distinctive features such as floes, open-water leads

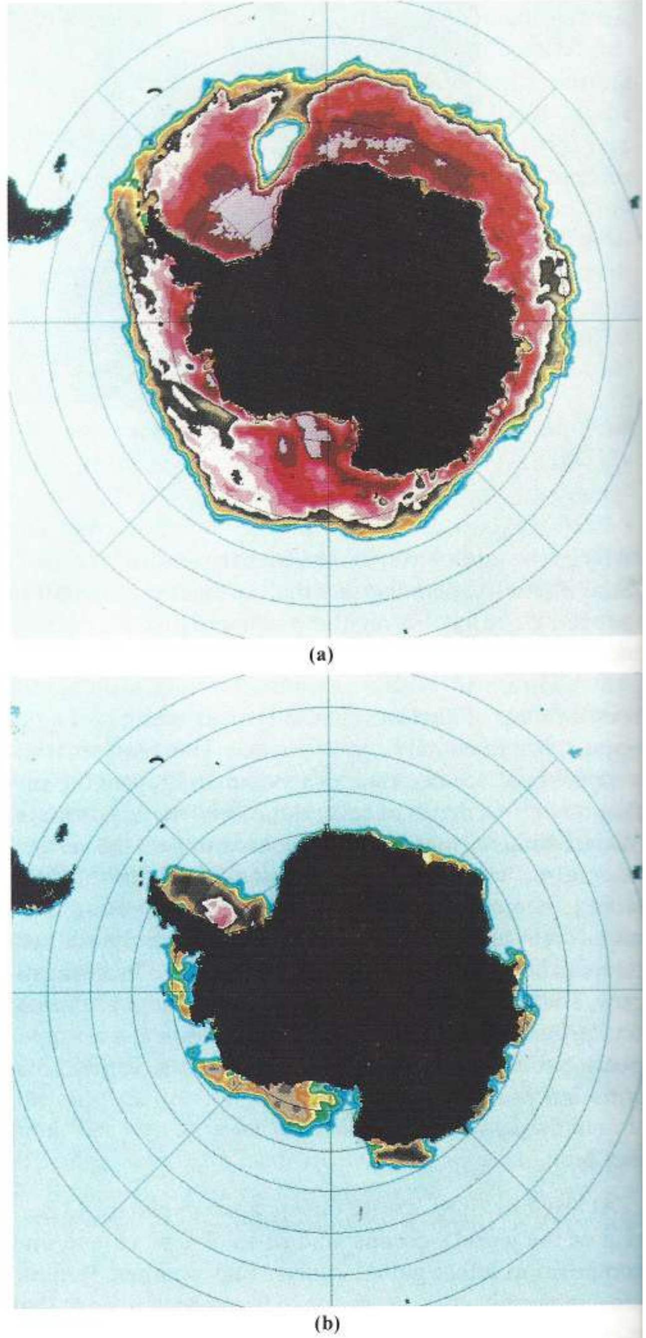
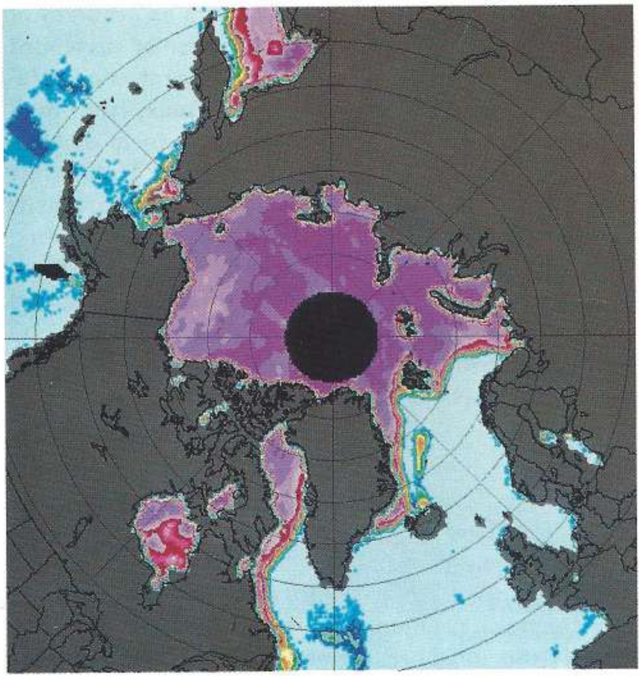
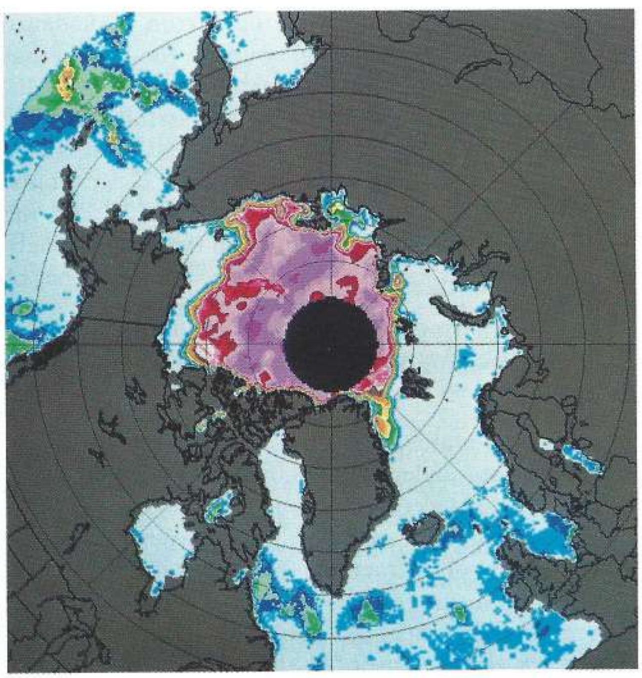


Fig. 8-5: Seasonal variation in Antarctic sea ice cover, from the NASA Nimbus 5 ESMR sensor, (a) between the winter maximum in August 1976, and (b) the summer minimum in February 1976. Antarctica is overlaid in black; ice concentration decreases from high near the coast (reds) to low near the ice margins (blues) [9].



(a)



(b)

Fig. 8-6: Seasonal variation in the arctic ice cover, from the NASA Nimbus 7 SMMR, between the winter maximum in April(a), and the summer minimum in September 1979(b). Color coding shows maximum ice concentrations in dark purple thinning to red and yellow. Light blue areas are open ocean. Dark blue patches over ocean indicate heavy clouds or rain. The dark spot over the North Pole lacks data as Nimbus 7 does not traverse this area [1].

and ridges. Smooth new ice cannot be distinguished from open water by SAR, but such conditions do not constitute a navigation hazard. Sequential SAR data have identified changes in ice pack movement over a period of days.

Radar Altimetry

The altimeter and scatterometer offer the other two active microwave techniques for observing sea ice. Radar altimeters were aboard NASA's GEOS-3 (April 1975 to December 1978) and Seasat (July to October 1978) satellites, and had a footprint of about 12 km radius. On land the altimeter measured over 600 000 elevations on the Greenland and Antarctic ice sheets, revealing the surface topography of previously unexplored regions. Altimetry data over sea ice provided accurate estimates of the boundary between ice-covered and open water, along track lines directly below the spacecraft. Other altimetry missions include the U.S. Navy's Geosat (1985), the European Space Agency's ERS-1 (1988/89), and the U.S. Navy/NASA/NOAA joint mission NROSS (1989). The combined passive and active microwave measurements of sea ice provide both large, regional, and local views. These offer powerful tools which ultimately will give new insights into the impact of sea ice on global climate, as well as aid exploration activities in polar regions.

Living and Non-Living Marine Resources

Fisheries

The biological marine environment is characterized by high variability in time and space. As with most remote sensing applications, satellites have a major advantage for understanding marine ecological resources through their ability to observe synoptically large areas of the ocean at repeated intervals. In fisheries applications, the key questions for effective management are what are the distributions and abundance of the fish, their prey,

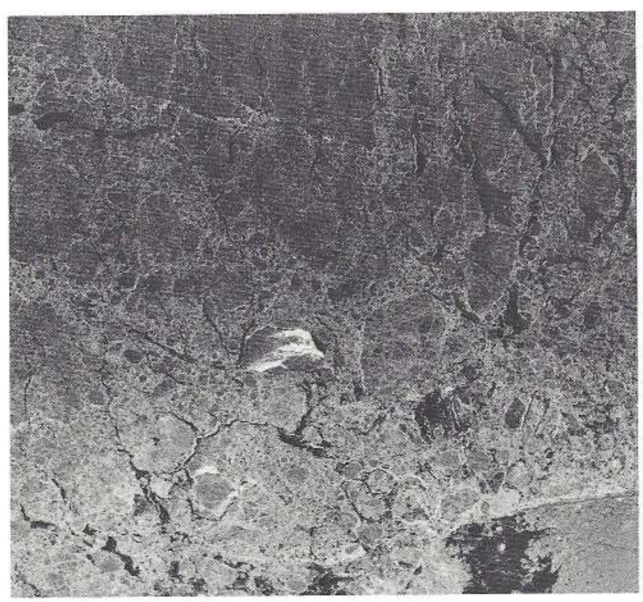


Fig. 8-7: Arctic pack ice in the Beaufort Sea, from the Seasat Synthetic Aperture Radar. Most pack ice is less than a few meters thick. The brighter object near the center of this 100 km area image is the ice island T-3, a 30 m thick tabular iceberg. Such images demonstrate the great potential for monitoring sea ice formation and movement [4].

and their predators? At the moment, satellites cannot answer most of these questions—for they represent basic marine ecological interactions, about which still little is known. But satellites do offer an important option to one problem biological oceanographers have always faced: the severe and costly limitations of ships as platforms for sampling the ocean.

The fluctuations in fish stocks are largely due to changing ocean conditions. Part of the goal of fishery management is to understand these variations, rather than average conditions, so that they can be modeled and related to environmental variables affecting fish populations.

Satellites enable scientists to view the entire oceans in a single day, and large regional areas in a few minutes. Fisheries applications use data from active and passive sensors aboard different satellites. Primary observations related to fisheries management have been surface color, temperature, and current, the latter based on the measurement of marine winds. From a research perspective the goal is to identify oceanic conditions which affect fisheries recruitment, distribution, abundance, and harvest. From the fisherman's practical perspective, there are a number of satellite remote sensing aids that are being developed which will help maximize their yields and minimize costly search time. And of course, fishermen need forecasts of general wind, wave, ice, and other environmental conditions, along with navigation, communication, and search and rescue systems, all of which depend to an increasing degree on spacecraft operations.

Ocean Color

Most marine organisms—from plankton to whales—tend to have patchy and irregular distributions. This feature further complicates identifying their distribution and abundance since ship searches are limited. At sea, *in situ* observations depend on nets and sonar. Though satellites are limited to observing only the sea surface, the launching of the coastal zone color scanner (CZCS) aboard Nimbus 7 in October 1978 offered biological oceanographers for the first time a powerful satellite tool in understanding ocean biological processes. The CZCS, however, does not directly measure fishery abundance and distribution. Instead it offers a more basic biological approach by measuring the intensity of sunlight backscattered from the upper meters of the ocean in four spectrally narrow color bands, in the blue, green, yellow, and red portions of the spectrum. Ocean color is primarily determined by the photosynthetic pigment, or chlorophyll concentrations, of microscopic drifting marine plants. These algae or phytoplankton are the basis of the entire marine food chain, and their pigments tend to absorb blue and red light. Therefore, the greener the water the greater the phytoplankton abundance. The CZCS scans and measures variations in ocean color from space at a resolution of 800 m, and computer processing of the resulting digital image data yields quantitative pictures of phytoplankton pigment concentrations.

The CZCS can measure pigment with an accuracy of about 35 percent, for water relatively free of suspended sediments. Since chlorophyll and pigment concentrations vary over three orders of magnitude, from hundredths of a milligram per cubic meter in most open ocean regions, to values exceeding ten in biologically active coastal areas, 35 percent accuracy measurements are exceedingly useful. Thus, the CZCS offers the first large-scale synoptic views of phytoplankton abundance and distribution. When combined with ship data, and data from other satellite sensors, these regional views will help us to understand processes affecting fish populations and to assess coastal water productivity.

Applications

Fisherman have trade secrets which help them locate prey. One useful indicator has been the abrupt ocean frontal boundaries which can occur between regions of different ocean color; these are zones where certain fish may congregate. Often these transition zones separate coastal from offshore regions. Coastal waters usually have higher phytoplankton abundance and productivity due to land runoff and coastal upwelling nutrient enrichment. The greater phytoplankton abundance results in more organisms higher up the food chain that feed on them, including commercially valuable fish. CZCS images have already been successfully used by commercial fisherman to help them increase their yields and decrease their search time by locating ocean fronts. Fisheries such as albacore tuna on the West Coast, the blue fin fishery on the East Coast, and the shrimp fishery on the Gulf Coast have all demonstrated the efficiency of directing operations using remote sensing.

Remote Sensing of Suspended Sediments and Pollutants

Surface pollutants, such as oil or other organic slicks, can be detected under certain conditions by remote sensors operating at electromagnetic wavelengths. At ultraviolet and visible wavelengths, oil slicks tend to have a higher index of refraction than background water. Depending on sun and viewing geometry, the slick can then reflect either more or less light than the neighboring areas back to the sensor. In the thermal infrared, the emissivity of oil differs from that of water. Oil slicks dampen small waves, causing microwaves to backscatter more vigorously from open water than from oil slick covered areas. To detect oil particles emulsified in the upper few meters of the water column, airborne laser fluorosensors are used. Satellite and airborne remote sensors are also being used to verify oil drift and dispersion models and study the capture of oil slicks by oceanographic fronts.

Substances further than a few meters down into the water column are more difficult to detect since water strongly absorbs most wavelengths outside the visible region, and scatters even visible light. Some pollutants are not detectable, but can be deduced only by associa-

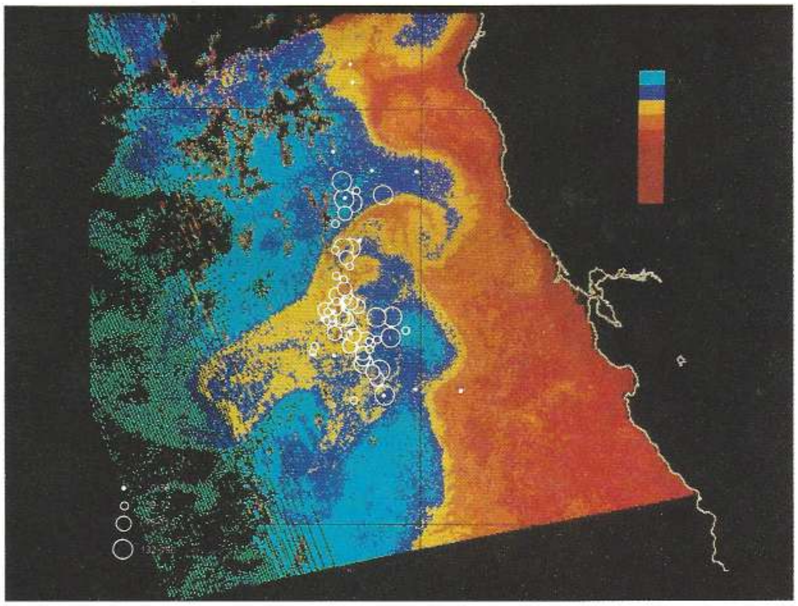


Fig. 8-8: Nimbus 7 CZCS water color image off the California coast on September 21, 1981, with greener near shore waters color-coded in red. Albacore tuna catches between September 19 and 24 noted by circles. The tuna are visual feeders, preferring clearer (blue) water areas immediately adjacent to more biologically active regions [6].

tion with other materials. Only a few substances can be detected and unambiguously identified by remote sensors alone. Generally, dissolved substances absorb certain spectral bands and thus change the color of the backscattered light. Suspended particulates, especially inorganic sediments, tend to reflect more energy, giving turbid waters a brighter appearance. Water bodies having different compositions can be identified by their colors and turbidities using simple color film in aerial cameras. Suspended sediment can also be used as a natural tracer to map current circulation patterns in turbid estuaries and coastal waters. However, to obtain a quantitative measure of pollutant concentrations, multispectral scanners must be used together with some carefully analyzed water samples obtained from boats.

Ocean-dumping wastes, such as industrial acid and municipal sewage sludge, have also been observed by Landsat and aircraft sensors. Principal component analysis of Landsat imagery obtained over New York Bight and off the coast of Delaware has enabled investigators to differentiate the types of ocean wastes dumped, and to determine their drift and dispersion. It is reasonable to conclude that aircraft and satellite sensors, when properly used in conjunction with boat measurements, enhance the ability to monitor certain pollutants and natural substances in water.

Marine Geophysics

Landsat and aircraft multispectral scanners have already shown their value in exploiting mineral resources on land. Remote ocean sensing for non-living marine resources, however, is still in a developmental stage. The two areas of exploration that are of greatest commercial interest are mineral and oil development. At present, the ocean remote sensing applications for offshore oil exploration and the submarine mining of minerals are rather limited. As we will show below, the limiting factor is the scale of resolution available in the currently available radar altimeter data; higher resolution will be required to identify details of important features such as rift zones and ridges showing submarine tectonic activity.

From its brief three-month life in 1978, the Seasat radar altimeter data has been used to generate global maps of the earth's gravity field. The radar altimeter generates pulses which reflect off the sea surface. From careful timing of their arrival back at the altimeter, the distance between the satellite and sea surface may be determined to a precision of about 6 cm. The actual relief of the sea surface is largely a measure of fluctuations in the earth's gravity field, since seamounts, or denser rocks beneath an otherwise flat sea bottom will cause the ocean surface to bulge upward by a measurable amount. Seasat data have been used to produce maps of the average sea surface topography, revealing valuable information about the composition and bathymetry of the ocean floor.

The structural trends which appear in these gravity maps may help direct oil exploration efforts. Their primary benefit is for a general reconnaissance prior to undertaking costly shipboard gravity and seismic surveys. Oil companies may wish to extend their knowledge of certain geological structures beyond previously explored areas. For example, if a fault has been mapped which seems promising for drilling, altimeter data may indicate how far that structure extends horizontally.

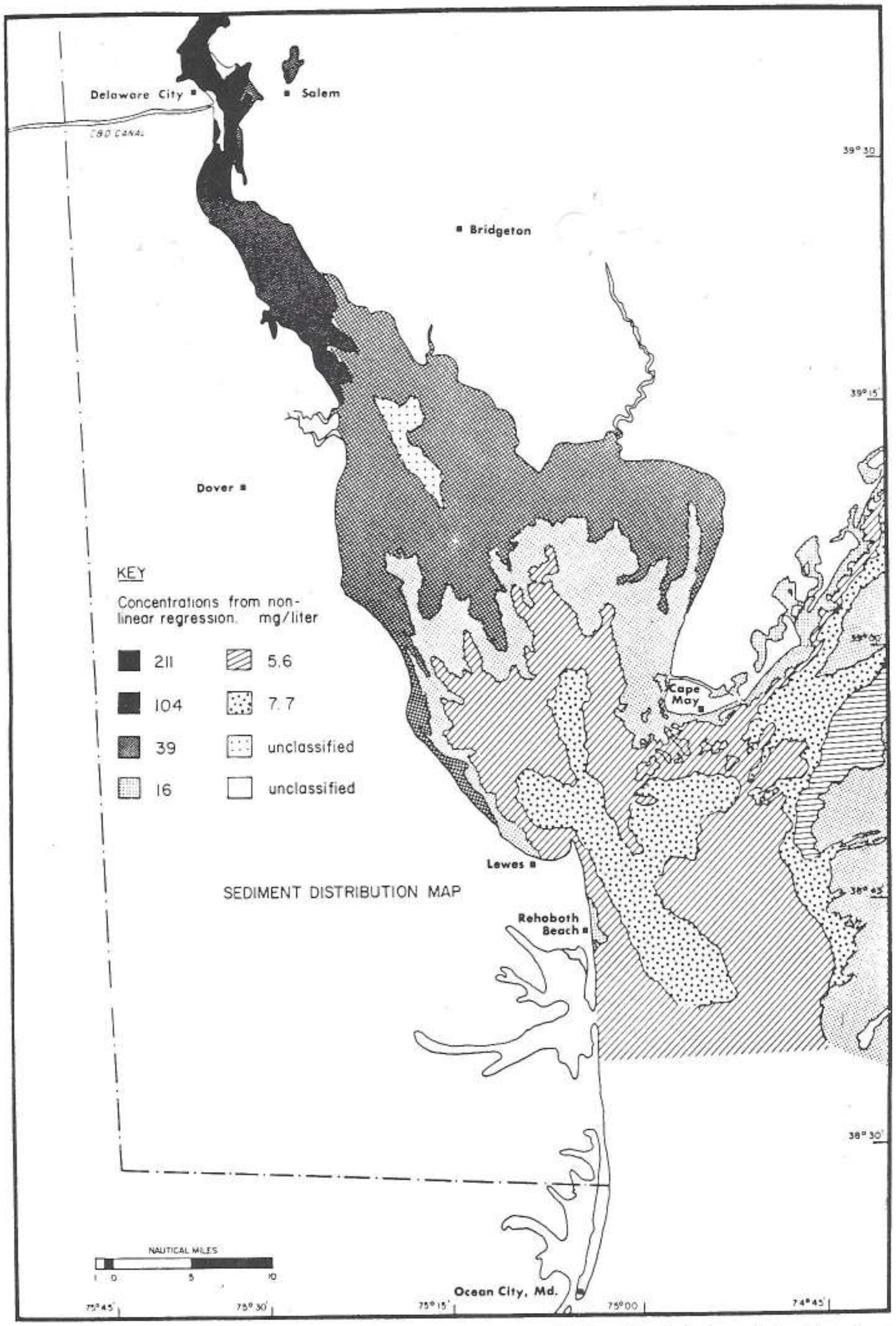


Fig. 8-9: A map of suspended sediment concentration for Delaware Bay, obtained by digital analysis of Landsat multi-spectral scanner imagery and correlation with 16 water samples obtained from boats and helicopters [5].

This would enable surveys to concentrate and maximize their search efforts. Identifying local gravity lows is also important, for they generally indicate thick sedimentary columns which may have oil-bearing potential.

From the Seasat mission, the presently available altimeter data coverage of the globe is limited to about 150 km resolution. (Resolution along any one trackline is only a few kilometers, but the separation between tracklines is 150 km). A U.S. Navy altimeter mission, Geosat, launched in 1985, will have an orbit designed to yield 18 km resolution, but the data will be classified and thus not available for a wide variety of potential applications. The European Space Agency is now considering a plan to operate its ERS-1 mission (1989 launch) in an orbit which would give 50 km resolution coverage. France and Japan also plan missions incorporating radar altimeters during the early 1990's. It thus appears that sometime within the next ten years, sufficiently dense coverage of the oceans by radar altimeters will have accumulated so that offshore oil and mining applications can be pursued.

Important Discoveries and Results

Only some of the many applications of ocean remote sensing, those that we believe are the most important or

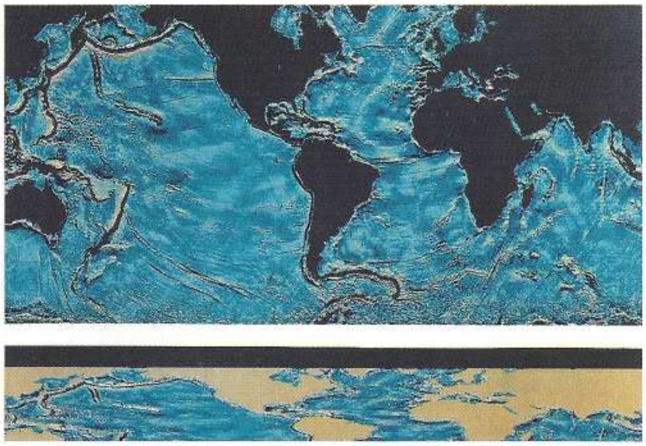


Fig. 8-10: Sea level variations, measured by the Seasat radar altimeter, are well-correlated with bathymetric relief and the earth's gravity field. Here the altimeter sea level data show the various midocean ridges, fracture zones, trenches, and chains of seamounts of the world ocean. Image produced by W. F. Haxby, Lamont-Doherty Geological Observatory.

illustrative, were selected for discussion in this chapter. The major point we wished to make was that the entire area of ocean remote sensing has made substantial progress along a very broad front of sensor technology, with applications extending to many aspects of ocean science and applications. No single discovery stands out; rather, a collection of techniques and capabilities from NASA research spacecraft has been demonstrated. The promises of the late 1960's and early 1970's have for the most part been tested and validated during the late 1970's and early 1980's. The result has been to lay a foundation for the next crucial step in making this technology available. This step will be putting in place systems for delivering sensor data on a long term, consistent, and easily accessible basis. Both ocean science and applications require the uninterrupted flow of data, the former to construct long-term series of global properties, and the latter to always have the data necessary to make tomorrow's forecast of marine conditions. NASA is now entering upon the next phase, of working in collaboration with other U.S. agencies, as well as with other nations, to design, build, launch, and operate the necessary spacecraft and sensors.

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