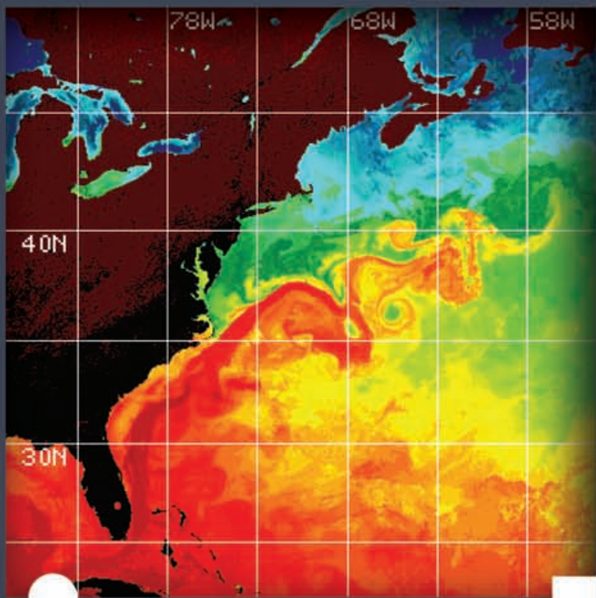


looking down on the seas

(without a drop of condescension)

HOW SATELLITES ARE REVOLUTIONIZING OUR UNDERSTANDING OF THE OCEAN

continents

(between the continents lie the oceans)

W E L C O M E

Dear Lecture Participant: On behalf of the Ocean Studies Board of the Nation-al Academies, I would like to welcome you to the Ninth Annual Roger Revelle Commemorative Lec-ture. This lecture was created by the Ocean Studies Board in honor of Dr. Roger Revelle to highlight the important links between the ocean sci-ences and public policy.

ROGER REVELLE

For almost half a century, Roger Revelle was a leader in the field of oceanography. Revelle trained as a geologist at Pomona College and the University of California, Berkeley. In 1936, he received his Ph.D. in oceanography from the Scripps Institution of Oceanography. As a young naval officer, he helped persuade the Navy to create the Office of Naval Research (ONR) to support basic research in oceanography and was the first head of ONR's geophysics branch. Revelle served for 12 years as the Director of Scripps (1950-1961, 1963-1964), where he built up a fleet of research ships and initiated a decade of expeditions to the deep Pacific that challenged existing geological theory.

Revelle's early work on the carbon cycle suggested that the sea could not absorb all the carbon dioxide released from burning fossil fuels. He calculated the first continual measurement of atmospheric carbon dioxide, leading to a long-term record that makes present-day discussions on research on global warming possible and very valuable.

Revelle kept the issue of increasing carbon dioxide levels in front of a the public and spearheaded efforts to investi-gate the mechanisms and consequences of climate change.

Revelle left Scripps for critical posts as Science Advisor to the Department of the Interior (1961-1963) and as the first Director of the Center for Population Studies at Harvard (1964-1976). Revelle applied his knowledge of geophysics, ocean resources, and population dynamics to the world's most vexing problems: poverty, malnutrition, security, and education.

In 1957, Revelle became a member of the National Academy of Sciences to which he devoted many hours of volunteer service. He served as a member of the Ocean Studies Board, the Board on Atmospheric Sciences and Climate, and many committees. He also chaired a number of influential Academy studies on subjects ranging from the environmen-tal effects of radiation to understanding sea-level change.

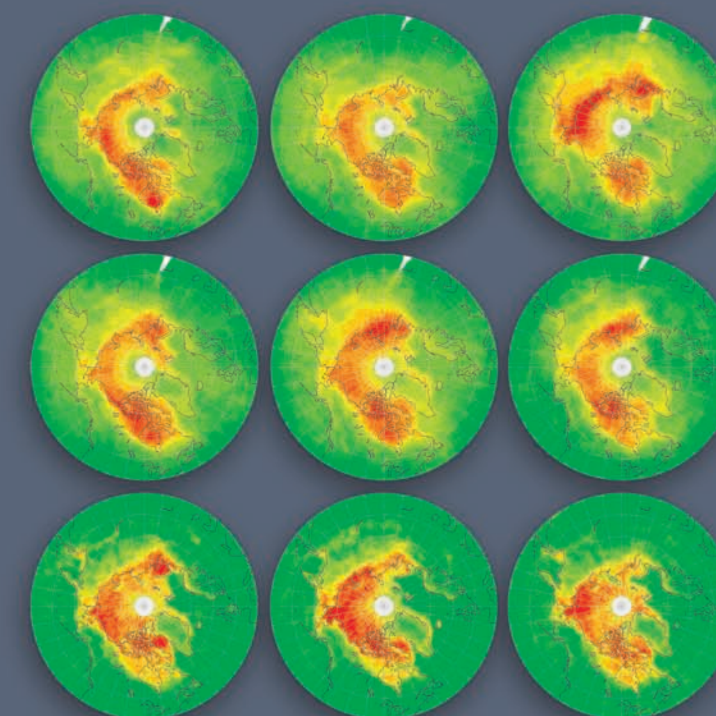
SMITHSONIAN NATIONAL MUSEUM OF NATURAL HISTORY The Ocean Studies Board is pleased to present the Revelle Lecture in cooperation with the Smithsonian National Museum of Natural History. Opened in 1910, the museum is dedicated to maintaining and preserv-ing the world's most extensive collection of natural history specimens and human arti-facts. It fosters critical scientific research, and presents educational programs and exhibi-tions that bring the work of scientists and curators to the public. The museum is part of the Smithsonian Institution, the world's largest museum and research complex. Dr. Paul Risser is the acting director. OCEAN SCIENCE INITIATIVE The National Museum of Natural History is building upon its substantial foundation in marine science to establish a com-prehensive Ocean Science Initiative that will: ■ Engage, educate, and inspire the public through state-of the-art displays in the Museum's exciting and ambitious new Ocean Hall, ■ Extend access to the exhibition, collections, and research through the integrated and dynamic Ocean Web Portal, and ■ Expand understanding of our oceans through the scholarly, multi-disciplinary Center for Ocean Science. TONIGHT'S LECTURE In the 50 years since the first satellite launch, space-based observations have played a key role in advanc-ing ocean science. Dr. Michael H. Freilich will describe how satellite observations reveal the ocean's role in Earth's climate. / Dr. Walter Munk, Revelle's distinguished colleague at Scripps Institution of Oceanography, will introduce the lecture. Among Dr. Munk's many honors are membership in the Royal Society and National Academy of Sciences (NAS), the NAS Agassiz Medal, the National Medal of Science, and the Kyoto Prize. Dr. Munk chaired the Ocean Studies Board from 1988-1985. / *Scripps will host the first west coast edition of the Revelle Lecture on February 28, 2008 in La Jolla, California.* SPONSORSHIP This lecture series would not be possible without the generous and continuing support of our sponsors: Office of Naval Research, U.S. Geological Survey, National Science Foundation, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, Smithsonian Institution, National Science Resources Center, and Scripps Institution of Oceanography. / I hope you enjoy tonight's event.

Shirley A Pomponi

Shirley Pomponi

CHAIR, OCEAN STUDIES BOARD

MICHAEL H. FREILICH, PH.D. is the Director of the Earth Science Division, in the Science Mission Directorate at NASA Headquarters. Prior to joining NASA, he was a Professor and Associate Dean in the College of Oceanic and Atmospheric Sciences at Oregon State University. He received his BS degrees in Physics (Honors) and Chemistry from Haverford College in 1975 and his Ph.D. in Oceanography from Scripps Institution of Oceanography in 1982. / Dr. Freilich's research focus is on using satellite-borne instruments to measure wind speeds and directions over the Earth's oceans. He was the team leader of the NASA Ocean Vector Winds Science Team and is a member of the QuikSCAT, SeaWinds, and Terra/AMSR Validation Teams. He has been honored with the JPL Director's Research Achievement Award (1988), the NASA Public Service Medal (1999), and the American Meteorological Society's Verner E. Suomi Award (2004), as well as several NASA Group Achievement awards. In 2004, he was named a Fellow of the American Meteorological Society. Dr. Freilich's non-scientific passions include nature photography and refereeing soccer at the youth, high school, and adult levels.



Ozone depletion at the North Pole is due in part to an increase in atmospheric bromine oxide (shown as orange-red), a compound vaporized from seawater when the sun returns to the Arctic in spring. FIGURE COURTESY OF A. RICHTER AND J.P. BURROWS, UNIVERSITY OF BREMEN, GERMANY.

BACKGROUND ON THE TRANSFORMATION OF OCEAN SCIENCE BY SATELLITE OBSERVATIONS

The following text is adapted from the 2008 National Research Council report *Earth Observations from Space: The First 50 Years of Scientific Achievements*
The complete report is available at: www.nap.edu/catalog/11991.html

Observations from space have fundamentally transformed the way we view our home planet. The capability of satellites has expanded tremendously from simple images to time-lapse animations and precise, quantitative measurements of Earth's properties. As this capability has grown, so has the potential for satellite observations to answer fundamental questions about the properties of the ocean, atmosphere, and land that will help us understand the processes and implications of global change.

OCEAN DYNAMICS

Due to the remoteness of the vast open oceans, satellites provided the first truly global ocean-observing system. Presatellite observing platforms included ships, moorings, drifters, and other tools, none of which could provide ocean basin-scale coverage at the temporal and spatial scales required to resolve the dynamic nature of the ocean that has been revealed since. In fact, even a well-known and studied current such as the Gulf Stream was not fully characterized until satellite observations were available (Box 1, Figures 1 and 2). Satellite data from scatterometers, altimeters, infrared radiometers, and various ocean color sensors opened up a new window for observing and quantifying how and why water moves around in the ocean (ocean dynamics) and how energy is exchanged between the ocean and atmosphere (air-sea interaction).

As illustrated in more detail below, sea surface temperature (SST) measurements not only revealed important information about ocean circulations (e.g., the Gulf Stream) but also advanced climate research by providing detailed information on the heat input into the ocean. Ocean color combined with SST observations led to new discoveries about the physical-biological coupling in the ocean, with important implications for the ocean's role in the carbon cycle. Observations from altimeters have revolutionized the field of oceanography, although it has taken about a decade for their contributions to be broadly recognized coincident with the steady increase in the accuracy of the sensors. Altimetry embedded within other modern ocean measurements and models yielded a virtually complete description of first-order physical processes in the ocean. The measurements provided real surprises to physical oceanographers, including detection of the internal tide in the open ocean, a highly variable surface ocean full of eddies, and measurements of global sea-level trends with an accuracy of millimeters per year. Combining satellite data with direct measurements of ocean properties using models has converted physical oceanography into a global science with true predictive skill.

THE OCEAN'S ROLE IN CLIMATE CHANGE

Sea surface temperature (SST) is one of the most important indicators of global climate change and represents a vital parameter for climate modeling (Hurrell and Trenberth 1999). The Advanced Very High Resolution Radiometer (AVHRR) used to monitor SST has had tremendous impact on the field of oceanography (Robinson 1985). Since the launch of the TIROS-N satellite in1978, SST data has been collected and used for a broad range of oceanographic research questions, including studies of regional climate variability, most notably the El Niño phenomenon, climate change, and ocean currents.

More than 80 percent of the total heating of the Earth system is stored in the ocean; this heat is dynamically transferred between the ocean and atmosphere while ocean currents redistribute heat from the tropics to the poles. Consequently, "if [scientists] wish to understand and explain [global] warming, the oceans are clearly the place to look," (Barnett et al. 2005). In addition, SST is central in coupling the ocean with the atmosphere and is a controlling factor in the heat and vapor exchange between the two (Johannessen et al. 2001). Trend analysis of SST provided evidence for global warming and the important climate-atmosphere feedback in the tropics that is also responsible for El Niño events in the eastern tropical Pacific (Cane et al. 1997). SST observations coupled with direct measurements of water temperatures to a depth of 3,000 m, indicate that the ocean (and hence the Earth) is retaining more heat, providing evidence for anthropogenic global warming (Barnett et al. 2001, 2005).

Understanding the increase in SST with respect to climate change will also help in quantifying and predicting sea-level rise (Cabanes et al. 2001). Recent work suggests that thermal expansion of the upper 500 m of the ocean (water expands as temperature increases) can fully explain the sea-level rise of 3.2 (± 0.2) mm per year observed by the satellite TOPEX Poseidon (Cabanes et al. 2001).

OCEAN COLOR REVEALS DYNAMIC FEATURES

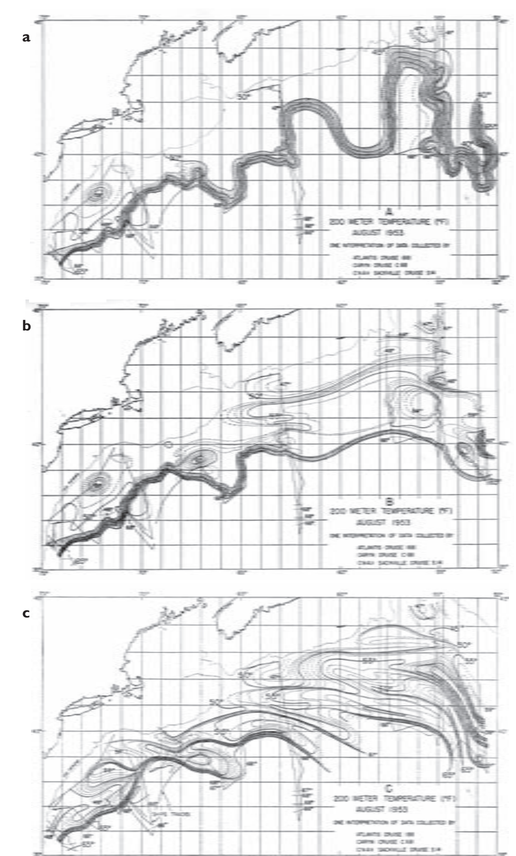
The Coastal Zone Color Scanner, launched aboard the Nimbus 7 satellite in 1978, provided the first satellite observations used to quantify chlorophyll concentration in the upper ocean. Chlorophyll is the major light-absorbing pigment in photosynthesis; it is used to estimate the biomass of marine algae and provides an indicator of the productivity of ocean waters around the world. The first images of surface chlorophyll distributions were truly astonishing, revealing much more spatial variability than expected based on measurements taken before satellites (Figure 3). The availability of global maps of chlorophyll has opened new avenues of research and changed the course of biological oceanography in many ways (Box 2, Figure 4).

Mesoscale features such as vortices and jets, as well as tidal fronts and river plumes, were known from aerial photographs and thermal imagery from the TIROS satellites, but ocean color images revealed entirely new features. An example of this is the vast extent of the Amazon River plume stretching many thousands of kilometers across the Atlantic (Figure 5, Muller-Karger et al. 1988). The plume's temperature does not provide sufficient contrast with the tropical Atlantic to be distinguished in thermal imagery, whereas the difference in color makes it clearly visible. In another application, the temporal variability of plumes in satellite images of the Gulf of Mexico have been correlated with river discharge measurements from gauging stations (Salisbury et al. 2001, 2004), thus offering a method for studying the influences of rivers on the coastal ocean.

As a result of satellite images, scientists have gained a physical perspective and appreciation of the relationship of the

BOX 1 / PATH OF THE GULF STREAM

Describing the path of the Gulf Stream and other major ocean currents was an early challenge to physical oceanographers who based their interpretations on very sparse data collected from oceanographic ships. For example, using data from a multiship survey, Fuglister and Worthington (1951) proposed the Multiple Current Hypothesis, which suggested that an instantaneous chart of the Gulf Stream would show a number of disconnected filaments of current that change in time **(FIGURE 1)**. Furthermore, they concluded that three Gulf Stream configurations were possible: a single filament, a branching current with two filaments, or a number of irregular disconnected filaments. In subsequent years, ship data could not distinguish between these three and other interpretations. However, in the mid-1970s the synoptic view provided by satellite thermal infrared imagery clearly showed that the Gulf Stream was a single filament, although it follows a tortuous and path that changes over time **(FIGURE 2)**. Over many years broad views of the Gulf Stream were obtained via satellite radiometers. These results showed considerable interannual variability in the path of the stream based on the position of the "North Wall"-the boundary at which strong temperature gradients (fronts) occur between warm Gulf Stream waters and the colder waters of the Northwest Atlantic, demarcating the northernmost extent of the stream (Lee and Cornillon 1995). These interannual motions were subsequently shown to be important to fisheries (Olson 2001) and to the productivity of the Slope Sea (Schollaert et al. 2004).



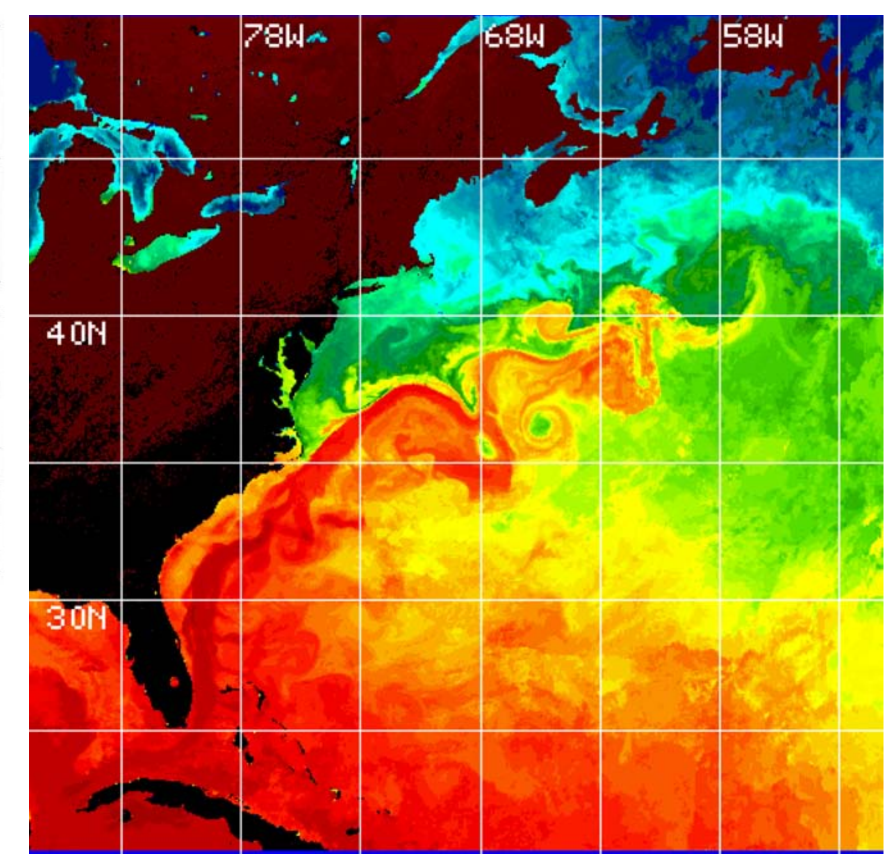


FIGURE 1 (Left) Fuglister's multiple current hypothesis. SOURCE: STOMMEL (1965). **FIGURE 2** (Right) Sea surface temperature image showing the Gulf Stream in the Atlantic Ocean. SOURCE: PROVIDED BY OTIS BROWN AND BOB EVANS.

ocean to land masses. Jets and filaments of water associated with major fronts along the continental shelf off California and the Pacific Northwest were a focus of the Coastal Transition Zone Program that used data from the Coastal Zone Color Scanner (Brink and Cowles 1991). These narrow filaments of high productivity water extended hundreds of kilometers seaward from the continental margin and are now recognized as important pathways for the transport of materials from the continental shelves to the deep ocean (Strub et al. 1991). Other researchers used the Coastal Zone Color Scanner to look at the Columbia River plume (Fiedler and Laurs 1990) and to document the relationship between the tuna catch and fronts and features seen in satellite images (Laurs et al. 1984).

UNDERSTANDING OCEAN TIDES: NEW SOLUTIONS TO AN OLD SCIENTIFIC QUESTION

Ocean tides have fascinated scientists since the early Greeks, but the first explanation was proposed by Isaac Newton who suggested that tides are caused by the gravitational attraction of the Moon and the Sun. A century later, Newton's theory was replaced by the dynamic response concept described by Laplace's tidal equation. However, analytical solutions to Laplace's tidal equation cannot be derived; thus, predicting ocean tides to some level of accuracy was made possible only by the empirical method developed by G.H. Darwin (son of Charles Darwin) in 1886. The behavior of ocean tides, particularly in the open ocean, remained elusive until the advent of satellite altimetry which measures the height of the surface of the ocean (Le Provost 2001). As described below, measurements of sea-surface height (SSH) using satellite altimetry reveals many features of the ocean that would otherwise be difficult or impossible to detect.

Satellite altimetry allowed synoptic measurements (measurements made simultaneously over a broad area) of ocean tides in the global open ocean for the first time. Most of the advances in global ocean tide modeling have been made since the launch of ERS-1 in 1991 and TOPEX/Poseidon in 1992. Based on altimetry and tidal models, it is now possible to predict ocean tides globally, including in the deep ocean, with a precision of 2-4 cm over periods of several months to years (Le Provost 2001). Global information on tides has resulted in an improved ability to model and predict global ocean tides that would not have been possible without satellites. This in itself is a major achievement, resulting in improved tidal predictions – information that is valuable to port managers and the shipping industry.

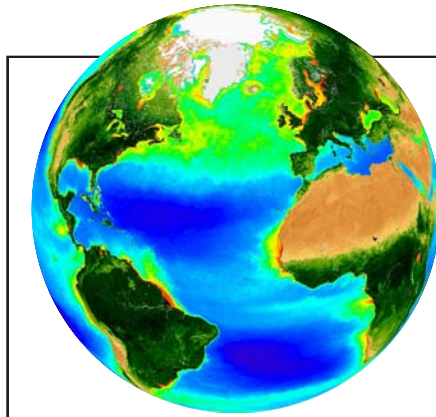


FIGURE 4 Map of chlorophyll *a* concentration (milligrams per cubic meter) in the upper Atlantic Ocean derived from data obtained by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS). SOURCE: SEAWIFS PROJECT, NASA GODDARD SPACE FLIGHT CENTER, AND GEOEYE.

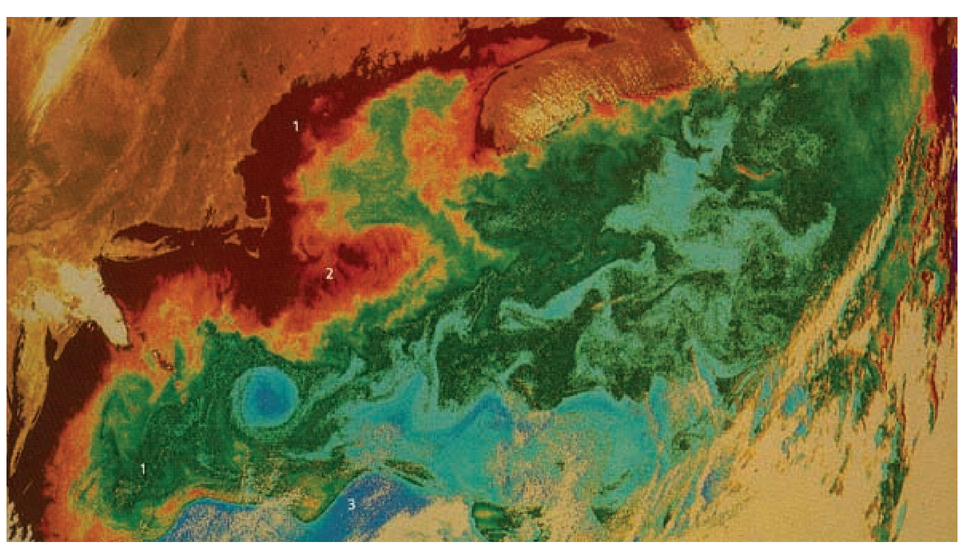
BOX 2 / GLOBAL MARINE BIOMASS FROM OCEAN COLOR

The ability to derive global maps of chlorophyll concentration in the upper ocean from satellite sensors was a groundbreaking achievement for the oceanographic community **(FIGURE 4)**. This biomass estimate can then be related to primary productivity and the marine carbon cycle. Although clouds prevent ocean color sensors from viewing the entire ocean surface on each orbital pass, a global picture of the distribution of photosynthetic plant biomass emerges from averaging data over several consecutive days or weeks.

The first ocean color sensor, Coastal Zone Color Scanner (CZCS), demonstrated that it is possible to detect subtle changes in the color of the ocean and relate these to the concentration of chlorophyll. Contrary to its name, the sensor was better at estimating biomass in the open ocean than in the coastal zone. Phytoplankton and dissolved organic matter are the primary sources of optical variability in the open ocean, whereas in coastal regions, mixtures of organic and inorganic materials affect ocean color. The problem of differentiating and quantifying individual constituents in the coastal ocean remains a challenge today.

The ocean color technology pioneered by the CZCS has been improved and incorporated into modern space instruments. The first modern global ocean color sensor was Japan's Ocean Color and Temperature Sensor (OCTS) launched in August 1996 aboard the Advanced Earth Observing Satellite (ADEOS). The U.S. Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) followed in August 1997. SeaWiFS is owned by Orbital Sciences Corporation, with a guarantee from NASA to buy data for the scientific research community.

FIGURE 3 Coastal Zone Color Scanner (CZCS) image of phytoplankton pigments in the North Atlantic Ocean. CZCS was flown on the Nimbus 7 satellite launched in 1978. CZCS was the first sensor designed specifically for satellite observations of ocean color variations. One of the primary determinants of ocean color is the concentration of chlorophyll pigments in the water. High concentrations of chlorophyll (red and brown areas in the image) are seen along the continental shelf (1) and above Georges Bank (2) where the biological productivity is high. Intermediate concentrations of chlorophyll pigments are shown in green, and the lowest levels are blue. Notice that the Gulf Stream (3) and the warm core eddy to the north (blue circle) have very low concentrations, reflecting the fact that the stream and the Sargasso Sea to the south are relatively nutrient poor. SOURCE: NASA.



THE TURBULENT OCEAN

In the late 1990s, altimetry led to a paradigm shift in the way we think about global ocean circulation (Wunsch and Ferrari 2004). Before altimetry, the energy supply for ocean circulation was believed to be dominated by the large-scale, slow moving forces created by changes in water temperature and salinity that affect the buoyancy of surface waters. Since altimetry, scientists have learned that energy is provided to the general circulation primarily by winds and tides. Perhaps the greatest single conceptual change (still not universally understood) is that the ocean is an extremely time-dependent, turbulent environment, with no steady-state patterns.

This new view of ocean dynamics has implications for understanding how the ocean has influenced climate over geological time. Ocean dynamics are fundamental to understanding how heat is transferred between the ocean and atmosphere and how heat is moved from the tropics to the poles. New insights into the importance of tidal energy dissipation to ocean dynamics and to other characteristics of a turbulent ocean led to a new appreciation of the difficulty of trying to model the circulation of paleooceans based on proxies of scalar properties, such as temperature, inferred from ocean sediment cores (Wunsch 2007). Inaccurate descriptions of ocean circulation will lead to inaccurate models of climate change over geological time due to the dependence of the Earth's climate on ocean circulation (Wunsch 2007). New knowledge gained from satellite observations has the potential to greatly improve the accuracy of ocean circulation models in the future.

THE CONTRIBUTION OF INTERNAL TIDES TO OCEAN MIXING

Satellite altimetry also has revealed the ubiquity and importance of internal tides (submerged waves with the same periodicity as the lunar surface tides) in the open ocean. Although the importance of internal tides on the continental shelf has long been known, satellite observations of the open ocean tidal signal made it possible for scientists to calculate the contribution of internal tides to deep ocean mixing (Garrett 2003). This discovery not only transformed oceanography but also has major implications for climate change science.

Because internal tides result in a vertical surface displacement of only a few centimeters (a 1-cm surface elevation change corresponds to vertical displacements of isotherms of tens of meters) and are only on the order of 100 km long, early satellite altimetry measurements were not able to resolve such small variation in the sea surface height. With TOPEX/Poseidon, along-track analysis became possible with the availability of precise altimetry data leading to direct global measurements of internal tides (Tierney et al. 1998). Similar to tides at the ocean surface, internal tides spread as a wave within the ocean interior, and their amplitude has been shown to correlate well with features on the ocean bottom such as ridges and seamounts (Ray and Mitchum 1997). Internal tides are now considered equal to winds in generating energy for mixing.

Tides transfer 3.5 terawatts of energy from the Sun and the Moon to the ocean. The conventional view was that dissipation of this energy occurred on the continental shelves and was thus irrelevant to the general circulation of the ocean (Wunsch and

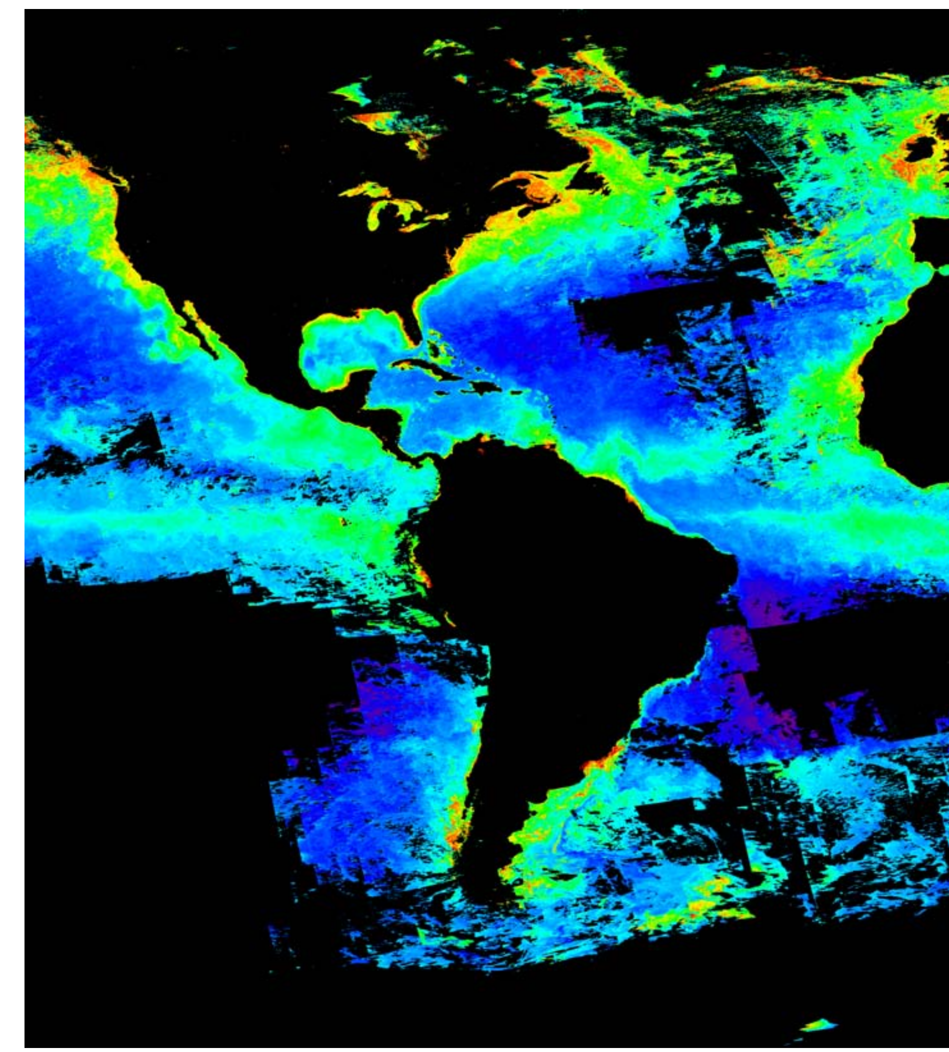


FIGURE 5 Early ocean color image shows plume of the Amazon River stretching across the Atlantic Ocean (Muller-Karger et al. 1988). The Amazon River plume is the green band extending thousands of kilometers into the Atlantic in this seasonally averaged Coastal Zone Color Scanner (CZCS) pigment image for the months of September to November 1979. Bands of high pigment also mark the nutrient-rich upwelling along the equator in the Pacific and Atlantic, and in high latitudes and coastal regions. Black areas over the ocean are missing data because the CZCS operated only intermittently. SOURCE: SEAWIFS PROJECT, NASA GODDARD SPACE FLIGHT CENTER, AND GEOEYE.

Ferrari 2004). An unexpected finding from altimetry measurements was that internal waves of tidal period were much more prevalent and of higher amplitude than previously believed (Egbert and Ray 2000). Calculations showed that as much as 1 terawatt of the 3.5- terawatt tidal energy input could be available to mix the deep ocean (Munk and Wunsch 1998). Much of the tidal energy released in the deep ocean occurs over ocean ridges, seamounts, and other features of abyssal topography. Altimetric internal tide measurements led directly to the current focus on understanding the energy sources for general ocean circulation and the insight that both winds and tides control circulation through mixing of abyssal waters. This concept had never even been discussed prior to about 1997.

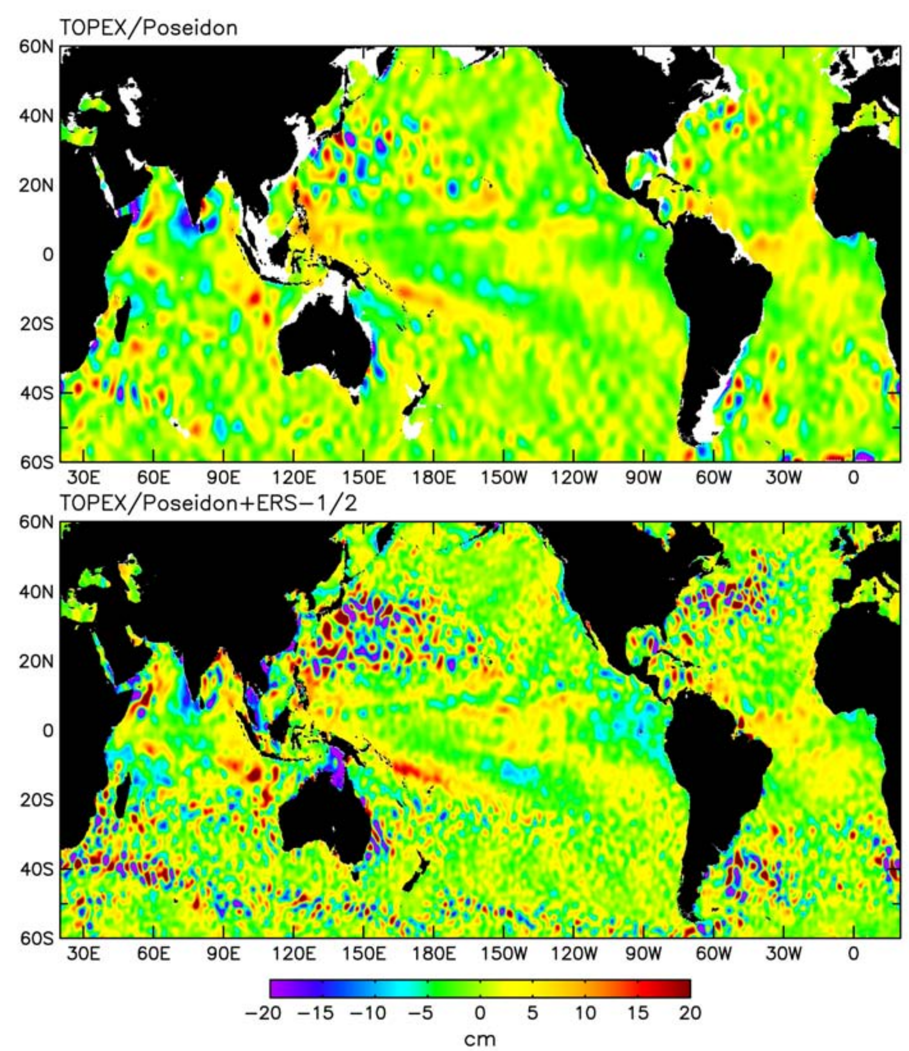
INSIGHTS ON OCEAN CIRCULATION: ROSSBY WAVES AND EDDIES

Based on theory, energy input to the ocean from wind and thermal forcing is expected to propagate westward in the form of Rossby waves. Rossby waves are large, slow-moving features that generally cross the ocean from east to west in the northern hemisphere. Typical wavelengths are 1,000 km and longer, measureable by sea surface height (SSH) signatures of about 10 cm. Although the existence of these waves had been accepted since the seminal studies by Rossby and his colleagues (1939, 1940), it took until the 1970s to collect enough data to verify this concept based on shipboard observations (vertical profiles of upper-ocean thermal structure in the North Pacific).

Satellite altimetry demonstrated the prevalence and thereby the importance of Rossby waves in ocean circulation—a central concept for understanding oceanic variability. The orbital configuration of the TOPEX/Poseidon altimeter was particularly well suited to study these features because this altimeter was designed to avoid aliasing by tides. A global synthesis of TOPEX/Poseidon data by Chelton and Schlax (1996; updated by Fu and Chelton 2001) detected the expected westward propagation in all ocean basins at speeds that varied with latitude. Thus, TOPEX/Poseidon altimetry provided compelling evidence supporting the theory that Rossby waves are an important mechanism for moving energy from east to west in ocean basins.

A new view is evolving due to the availability of simultaneous measurements of SSH by the TOPEX/Poseidon and the European Remote Sensing Satellite (ERS) altimeters. These simultaneous measurements allow the construction of much higher-resolution SSH fields than can be obtained from a single altimeter (Chelton et al. 2007b). By merging the TOPEX/Poseidon and ERS altimeter data sets, SSH fields are obtained with approximately double the spatial resolution of SSH fields constructed from TOPEX/Poseidon alone (Ducet et al. 2000, Figure 6). The newly merged data set in the lower panel of Figure 6 shows the intricate structure of the ocean circulation. The observations of the time-dependent motions visible in this figure led to a much clearer understanding of the role such motions play in ocean circulation that varies over time. At latitudes within about 25 degrees of the equator, a Rossby wave-like character is still evident in the merged data. At higher latitudes, however, the doubling of resolution reveals that the SSH field is much more eddylike in nature than suggested from maps constructed from only the TOPEX/Poseidon data (Chelton et al.

FIGURE 6 Discovery of open ocean eddies using satellite altimetry. Global maps of sea surface height (SSH) constructed from TOPEX/Poseidon data alone (top) and from the merged TOPEX/Poseidon and ERS data (bottom). After filtering to remove large-scale heating and cooling effects unrelated to mesoscale variability, the SSH data reveals many isolated cyclonic and anticyclonic features (negative and positive SSH, respectively). SOURCE: AFTER MALONEY AND CHELTON (2006).



2007b). These eddies generally propagate westward; cyclonic eddies tend to be deflected toward the poles and anticyclonic eddies tend to be deflected toward the equator. This discovery demonstrates that energy and other water properties are transported not only east–west by Rossby waves, but also north-south by eddies, a phenomenon that may have substantial implications for biological processes.

OCEAN WIND MEASUREMENTS REVEAL INTERPLAY OF OCEAN AND ATMOSPHERE

Scatterometers have also made significant contributions to the study of ocean dynamics by providing a synoptic view (approximately 25 km spatial resolution) of vector winds over the ocean. Scatterometers transmit a pulse of microwave energy towards the Earth's surface and measure the reflected energy to determine the amount of scatter, calculated as a function of the energy dissipated by the roughness of the surface. Scatterometry has provided insights into the exchange of heat and momentum between the atmosphere and ocean. Weather forecasting has been significantly improved by incorporating scatterometer-derived winds into forecasts. In particular, scatterometer data are useful for determining the location, strength, and movement of cyclones over the ocean. Furthermore, new insights into the underlying physics of air-sea interactions have changed our perception of ocean mixing, an important feature for understanding both the dynamics of ocean currents as well as the processes that support areas of high biological productivity.

Prior to the availability of scatterometry to measure ocean vector winds, most of what was known about the space-time variability of the wind field over the ocean was based on 10-m wind analyses from the European Centre for Medium-Range Weather Forecasts (ECMWF) and the U.S. National Centers for Environmental Prediction (NCEP) global numerical weather prediction models. Feature resolution in these models is limited to wavelength scales longer than about 500-km (Milliff et al. 2004, Chelton et al. 2006), despite the fact that winds from the QuikSCAT scatterometer have been assimilated into both of these models since January 2002. The resolution is even worse in the reanalysis of wind fields that are used in most models of ocean circulation and for most studies of climate variability. For example, the resolution limitation of the NCEP reanalysis winds is about 1,000-km (Milliff et al. 2004). Ocean-atmosphere interaction on the large scales resolvable by global atmospheric models is characterized by stronger winds over colder water (Kushnir 2002).

The QuikSCAT scatterometer data revealed that ocean-atmosphere interaction is fundamentally different on scales shorter than those resolved by global atmospheric models. Wherever strong sea surface temperature (SST) fronts occur, low-level winds are locally stronger over warm water and weaker over cold water (Xie 2004). This ocean-atmosphere interaction apparently arises from SST modifications of stability and vertical mixing in the marine atmospheric boundary layer. This is consistent with earlier shipboard measurements in the Gulf Stream (Sweet et al. 1981) and the Agulhas Current (Jury and Walker 1988) that showed enhanced vertical turbulent mixing as cold air passes over warm water. The mixing deepens the marine atmospheric boundary layer and transfers momentum downward from aloft to the sea surface, causing the surface winds to accelerate. Decreased mixing over cold water stabilizes and thins the marine atmospheric boundary layer, resulting in decreased surface winds. Wallace et al. (1989) hypothesized a similar SST influence on low-level winds in the eastern tropical Pacific based on historical observations of surface winds and SST from ships.

The SST influence on low-level winds has important implications for both the ocean and the atmosphere. The spatial variability of SST in the vicinity of meandering fronts induces curl (crosswind components) and divergence (downwind components) in surface wind stress at the site of the SST gradient (Chelton et al. 2004). An example of the influence of SST on the curl and divergence of the wind stress is shown in Figure 7 for the California Current region.

The wind stress curl is of particular interest because it generates the open-ocean upwelling and downwelling that drives ocean circulation and brings cold water and nutrients to the sea surface. Moreover, SST-induced wind mixing and wind stress curl in turn change the SST, resulting in a two-way coupling between the ocean and the atmosphere, with implications for both the physics and the biology of the ocean. ●

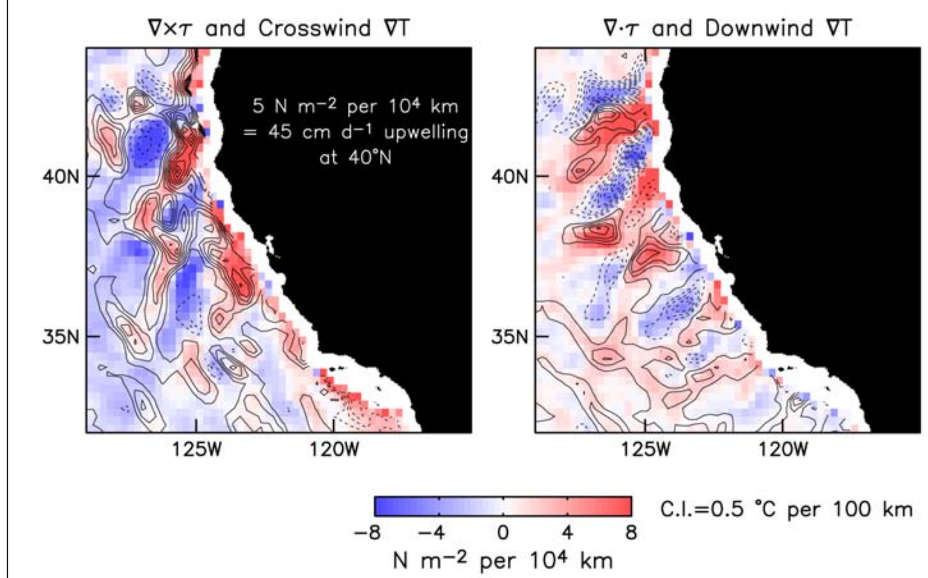


FIGURE 7 Dynamics of the coastal ocean. Averages of wind stress curl with contours of crosswind sea surface temperature (SST) gradient (left) and wind stress divergence with contours of downwind SST gradient (right) over the California Current system in September 2004. Satellite microwave measurements of SST are not well suited to studies in this region because of the coarse (~50 km) resolution and the inability to measure SST within about 75 km of the coastline. SOURCE: CHELTON ET AL. (2007A).

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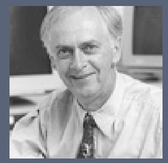

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