How satellites are revolutionizing our understanding of the ocean

looking down on the seas

(without a drop of condescension)
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The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy’s purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.
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 the public and spearheaded efforts to investigate 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 environmental effects of radiation to understanding sea-level change.
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.

Ocean studies board

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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. Pre-satellite 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 radimeters, and various other tools provided new avenues of research and changed the course of biological oceanography in many ways (Box 2, Figure 4).

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 in 1978, 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, 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). SST data 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 perspective of current that change in time and space (Figure 1). Furthermore, they concluded that these Gulf Stream configurations were possible: a single filament, a branching current with two filaments, or a number of irregularly connected 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 satellites 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 radimeters. These results showed considerable interannual variability in the path of the stream based on the position of the “North-WAT” 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 (Liu and Carmill 1995). These interannual motions were subsequently shown to be important to fisheries (Olson 2001) and to the productivity of the Slope Sea (Schillhart et al. 2004).

**THE OCEAN’S ROLE IN CLIMATE CHANGE**

Sea surface temperature (SST) is one of the most important indicators of global climate change. SSTs can 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 ocean to the atmosphere.
TIDES: NEW SOLUTIONS TO AN OLD SCIENTIFIC QUESTION

Ocean tides have fascinated scientists for centuries, with early Greeks, such as Aristotle, and later scholars like Archimedes, exploring their nature and predicting their effects. However, it was not until the 17th century that Isaac Newton proposed a theory to explain tides, suggesting they are caused by the gravitational attraction between the Sun and the Moon. Newton's work laid the foundation for understanding tidal phenomena, but the precise prediction of tides was not achieved until the advent of satellite altimetry in the late 20th century.

Newton's theory of gravity, which proposed that the force of gravity decreases with distance, was revolutionary. It provided a framework for understanding how objects in the solar system are influenced by gravitational forces. This concept was later extended and applied to the study of tides, which are the result of the interaction between the gravitational forces of the Sun and the Moon and the rotation of the Earth.

The ability to derive global maps of chlorophyll concentration from satellite sensors was a groundbreaking achievement for the oceanographic community. This technology has enabled researchers to study the distribution of phytoplankton, which are tiny marine plants that form the base of the food chain in marine ecosystems. By monitoring chlorophyll levels, scientists can track the productivity of the ocean and understand the dynamics of marine ecosystems.

The advent of satellite altimetry has significantly advanced our understanding of ocean tides. This technology measures the height of the surface of the ocean relative to a reference plane, allowing scientists to track the movement of ocean water over time and space. With data from missions like ERS-1 and TOPEX/Poseidon, researchers have been able to map ocean tides with unprecedented detail and accuracy, revealing many features of the ocean surface that were previously unknown.

Satellite altimetry has also provided new insights into the importance of tidal energy dissipation to ocean dynamics. Tides are a result of the gravitational pull of the Moon and the Sun on the Earth's oceans. This movement of water not only influences weather and climate but also has implications for marine life and human activities. By understanding how energy is dissipated during tides, scientists can better predict ocean tides and their effects on coastal environments.

The Ubiquity and Importance of Internal Tides

Internal tides are ocean tides that occur beneath the surface of the water. They are caused by the gravitational forces of the Moon and the Sun on the Earth's oceans, leading to variations in water temperature and salinity. These tides can have significant impacts on marine ecosystems, including the distribution of nutrients and the transport of heat and other materials across the ocean.

The ability to model and predict global ocean tides has been crucial in improving our understanding of the Earth's climate and weather. By understanding the dynamics of internal tides and their effects on ocean circulation, scientists can make more accurate predictions about climate change and weather patterns. This information is vital for emergency management and the shipping industry, as well as for understanding the impacts of climate change on marine ecosystems.

In conclusion, the advancement of satellite technology has revolutionized our understanding of ocean tides. The ability to track changes in ocean tides with precision and accuracy has led to new insights into the importance of tidal energy dissipation and the role of internal tides in shaping marine ecosystems.

FIGURE 3 Coastal Zone Color Scanner (CZCS) image of phytoplankton pigments in the North Pacific 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.

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

FIGURE 5 Early ocean color image shows plume of the Amazon River stretching across the Atlantic Ocean (Molle-Karger et al. 1998). The Amazon River plume is the green band extending thousands of kilometers into the Atlantic Ocean 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 GEOTECH.
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 propagates 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, slowly varying features that generally cross the ocean from east to west in the northern hemisphere. Typical wavelengths are 1,000 km and longer, measureable by northern hemisphere. Typical wavelengths cross the ocean from east to west in the form of Rossby waves. Rossby waves are could be available to mix the deep ocean (Egbert and Ray 2000). An unexpected finding from altimetry measurements was that internal tides control circulation through mixing of abyssal waters. This concept had never even been discussed prior to about 1997.

FIGURE 6 Discovery of open ocean eddies using satellite altimetry. Global maps of sea surface height (SSH) constructed from TOPEX/Posidon data alone (top) and from the merged TOPEX/Posidon 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 MALINOTI and CHELTON (2007).

A new view is evolving due to the availability of simultaneous measurements of SSH by the TOPEX/Posidon 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/Posidon and ERS data sets, SSH fields are obtained with approximately double the spatial resolution of SSH fields constructed from TOPEX/Posidon 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/Posidon data (Chelton et al. 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 (approxim- ately 25-35 km 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 environments, approved 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 and as well as the processes that support areas of high biological productivity.

Prior to the availability of scatterometer data to complement SST-influenced 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 in the eastern trop- ical 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 meander- ing 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 this process is when a 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.
REFERENCES


