macrofauna require sophisticated sensory responses to maintain an optimum position on the beach and the ability to react appropriately to the conditions and circumstances they encounter on their particular beach. Finally, energy conservation is essential, so that metabolic, biochemical adaptations are ultimately dictated by an erratic food supply, again dependent on water movements.

See also

Beaches, Physical Processes Affecting. Diversity of Marine Species. Large Marine Ecosystems. Microbial Loops. Network Analysis of Food Webs. Ocean Gyre Ecosystems. Polar Ecosystems. Storm Surges. Tides. Upwelling Ecosystems.

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SATELLITE ALTIMETRY

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Introduction

Students of oceanography are usually surprised to learn that sea level is not very level at all and that the dominant force affecting ocean surface topography is not currents, wind, or tides; rather it is regional variations in the Earth's gravity. Beginning in the 1970s with the advent of satellite radar altimeters, the large-scale shape of the global ocean surface could be observed directly for the first time. What the data revealed came as a shock to most of the oceanographic community, which was more accustomed to observing the sea from ships. Profiles telemetered back from NASA's pioneering altimeter, Geos-3, showed that on horizontal scales of hundreds to thousands of kilometers, the sea surface is extremely complex and bumpy, full of undulating hills and valleys with vertical amplitudes of tens to hundreds of meters. None of this came as a surprise to geodesists and geophysicists who knew that the oceans must conform to these shapes owing to spatial variations in marine gravity. But for the oceanographic community, the concept of sea level was forever changed. During the following two decades, satellite altimetry would provide exciting and revolutionary new insights into a wide range of earth science topics including marine gravity, bathymetry, ocean tides, eddies, and El Niño, not to mention the marine wind and wave fields which can also be derived from the altimeter echo. This chapter briefly addresses the technique of satellite altimetry and provides examples of applications.

Measurement Method

In concept, radar altimetry is among the simplest of remote sensing techniques. Two basic geometric measurements are involved. In the first, the distance between the satellite and the sea surface is determined from the round-trip travel time of microwave pulses emitted downward by the satellite's radar and reflected back from the ocean. For the second measurement, independent tracking systems are used to compute the satellite's three-dimensional position relative to a fixed Earth coordinate system. Combining these two measurements yields profiles of sea surface topography, or sea level, with respect to the reference ellipsoid (a smooth geometric surface which approximates the shape of the Earth).

In practice, the various measurement systems are highly sophisticated and require expertise at the cutting edge of instrument and modeling capabilities. This is because accuracies of a few centimeters

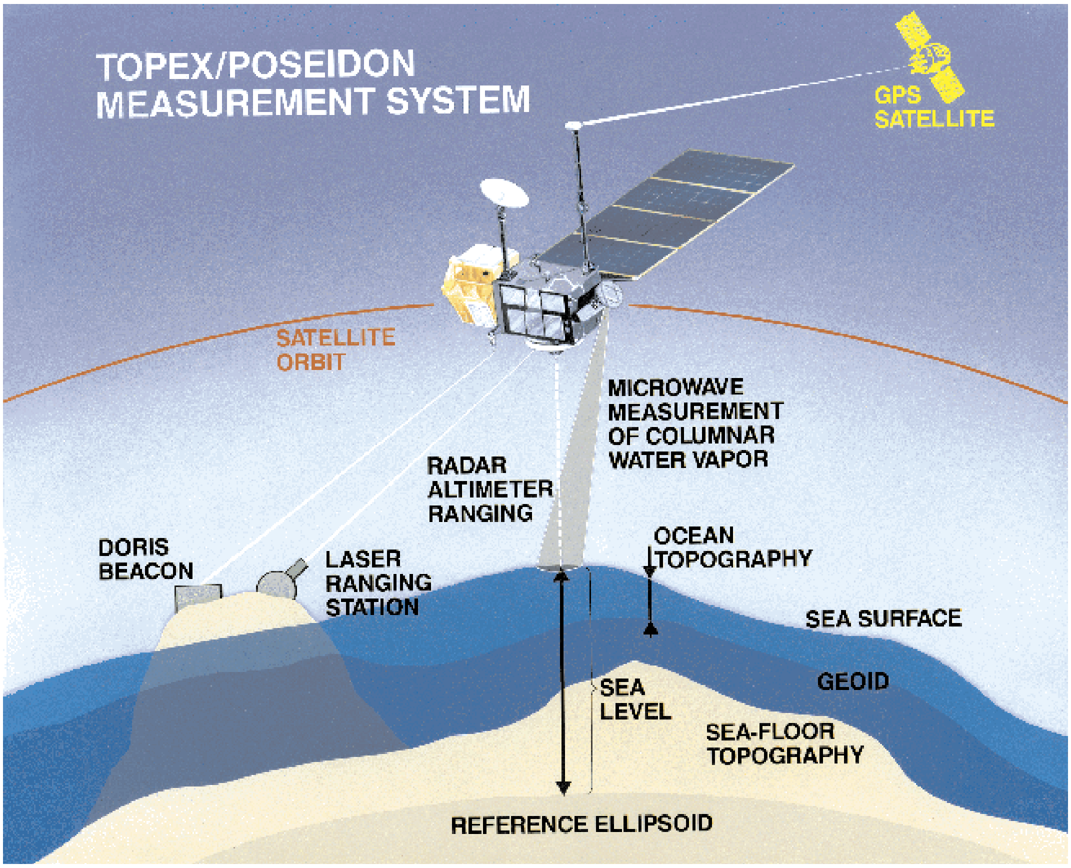

Figure 1 Schematic diagram of satellite radar altimeter system. Range to the sea surface together with independent determination of the satellite orbit yields profiles of sea surface topography (sea level) relative to the Earth's reference ellipsoid. Departures of sea level from the geoid drive surface geostrophic currents.

must be achieved to properly observe and describe the various oceanographic and geophysical phenomena of interest. **Figure 1** shows a schematic of the Topex/Poseidon (T/P) satellite altimeter system. Launched in 1992 as a joint mission of the American and French Space agencies (and still operating as of 2001), T/P is the most accurate altimeter flown to date. Its microwave radars measure the distance to the sea surface with a precision of 2 cm. Two different frequencies are used to solve for the path delay due to the ionosphere, and a downward-looking microwave radiometer provides measurements of the integrated water vapor content which must also be known. Meteorological models must be used to estimate the attenuation of the radar pulse by the atmosphere, and other models correct for biases created by ocean waves. Three different tracking systems (a laser reflector, a Global Positioning System receiver, and a 'DORIS' Doppler receiver) determine the satellite orbit to within 2 cm in the radial direction. The result of all these measurements is a set of global sea level observations with an absolute accuracy of 3–4 cm at intervals of 1 s, or about 6 km, along the satellite track. The altimeter footprint is exceedingly small – only 2–3 km – so regional maps or 'images' can only be derived by averaging data collected over a week or more.

Gravitational Sea Surface Topography

Sea surface topography associated with spatial variations in the Earth's gravity field has vertical amplitudes 100 times larger than sea level changes generated by tides and ocean currents. To first order, therefore, satellite altimeter data reveal information about marine gravity. Within 1–2% the ocean topography follows a surface of constant gravitational potential energy known as the geoid or the equipotential surface, shown schematically in **Figure 1**. Gravity can be considered to be constant in time for most purposes, even though slight changes do occur as the result of crustal motions, redistribution of terrestrial ice and water, and other slowly varying phenomena. An illustration of the

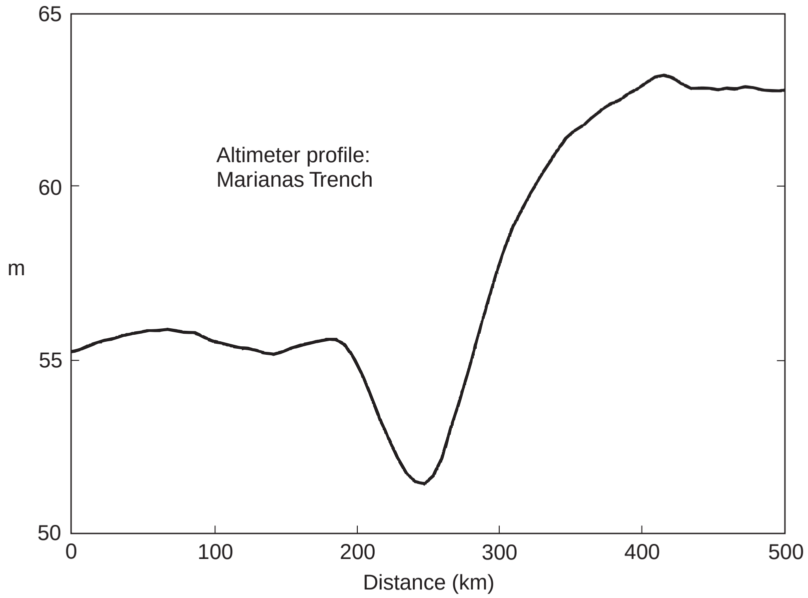

Figure 2 Sea surface topography across the Marianas Trench in the western Pacific measured by Topex/Poseidon. Heights are relative to the Earth's reference ellipsoid.

gravitational component of sea surface topography is provided in **Figure 2**, which shows a T/P altimeter profile collected in December 1999 across the Marianas Trench in the western Pacific. The trench represents a deficit of mass, and therefore a negative gravity anomaly, so that the water is pulled away from the trench axis by positive anomalies on either side. Similarly, seamounts represent positive gravity anomalies and appear at the ocean surface as mounds of water. The sea level signal created by ocean bottom topography ranges from ~1 m for seamounts to ~10 m for pronounced features like the Marianas Trench, and the peak-to-peak amplitude for the large-scale gravity field is nearly 200 m.

Using altimeter data collected by several different satellites over a period of years, it is possible to create global maps of sea surface topography with extraordinary accuracy and resolution. When these maps are combined with surface gravity measurements, models of the Earth's crust, and bathymetric data collected by ships, it is possible to construct three-dimensional images of the ocean floor – as if all the water were drained away (**Figure 3**). For many oceanic regions, especially in the Southern Hemisphere, these data have provided the first reliable maps of bottom topography. This new data set has many scientific and commercial applications, from numerical ocean modeling, which requires realistic bottom topography, to fisheries, which have been able to take advantage of new fishing grounds over previously uncharted seamounts.

Dynamic Sea Surface Topography

Because of variations in the density of sea water over the globe, the geoid and the mean sea surface are not exactly coincident. Departures of the sea surface with respect to the geoid have amplitudes of about 1 m and constitute what is known as 'dynamic topography'. These sea surface slopes drive the geostrophic circulation: a balance between the surface slope (or surface pressure gradient) and the Coriolis force (created by the Earth's rotation). The illustration in **Figure 4** shows an estimate of the global geostrophic circulation derived by combining a mean altimeter-derived topography with a geoid computed from independent gravity measurements. Variations are between −110 cm (deep blue) and 110 cm (white). The surface flow is along lines of equal dynamic topography (red arrows). In the Northern Hemisphere, the flow is clockwise around the topography highs, while in the Southern Hemisphere, the flow is counter-clockwise around the highs. The map shows all the features of the general circulation such as the ocean gyres and associated western boundary currents (e.g. Gulf Stream, Kuroshio, Brazil/Malvinas Confluence) and the Antarctic Circumpolar Current.

At the time of writing, global geoid models are not sufficiently accurate to reveal significant new information about the surface circulation of the ocean. However, extraordinary gravity fields will soon be available from dedicated satellite missions

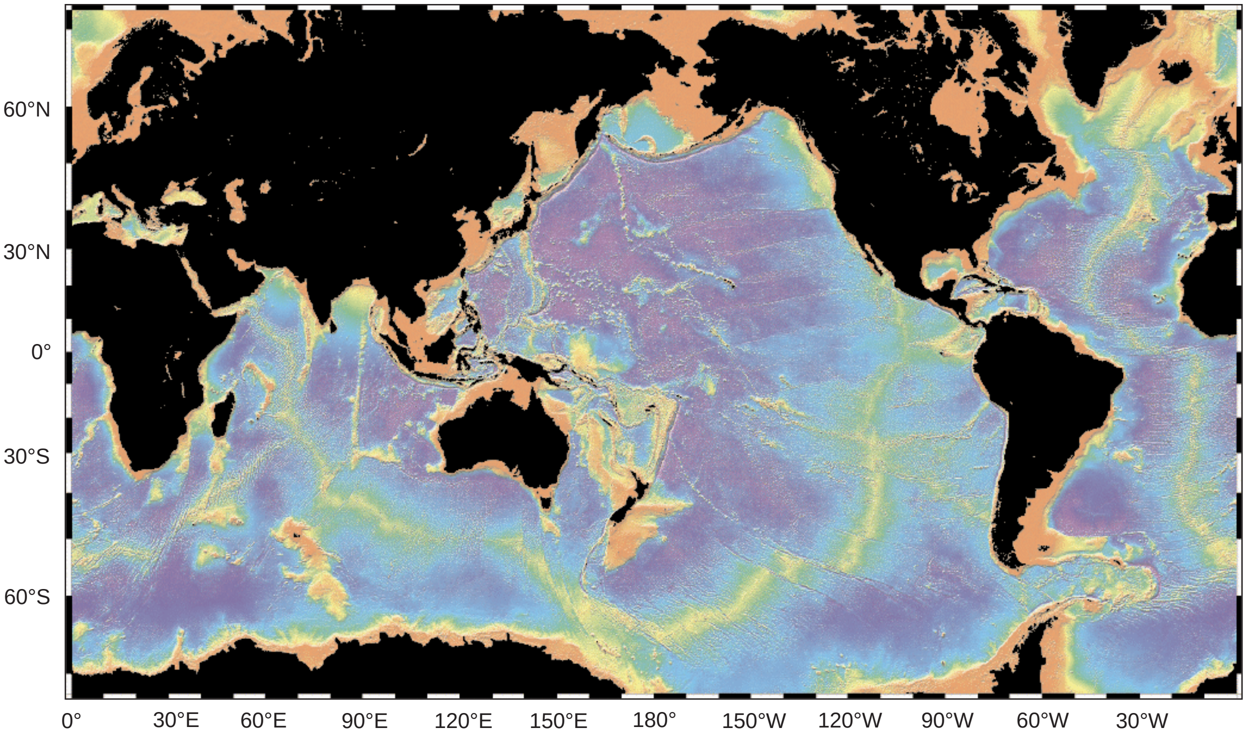

Figure 3 Topography of the ocean bottom determined from a combination of satellite altimetry, gravity anomalies, and bathymetric data collected by ships. (Courtesy of Walter H. F. Smith, NOAA, Silver Spring, MD, USA.)

such as the Challenging Minisatellite Payload (CHAMP: 2000 launch), the Gravity Recovery and Climate Experiment (GRACE: 2002 launch), and the Gravity Field and Steady-state Ocean Circulation Explorer (GOCE: 2005 launch). These satellite missions, sponsored by various agencies in the USA

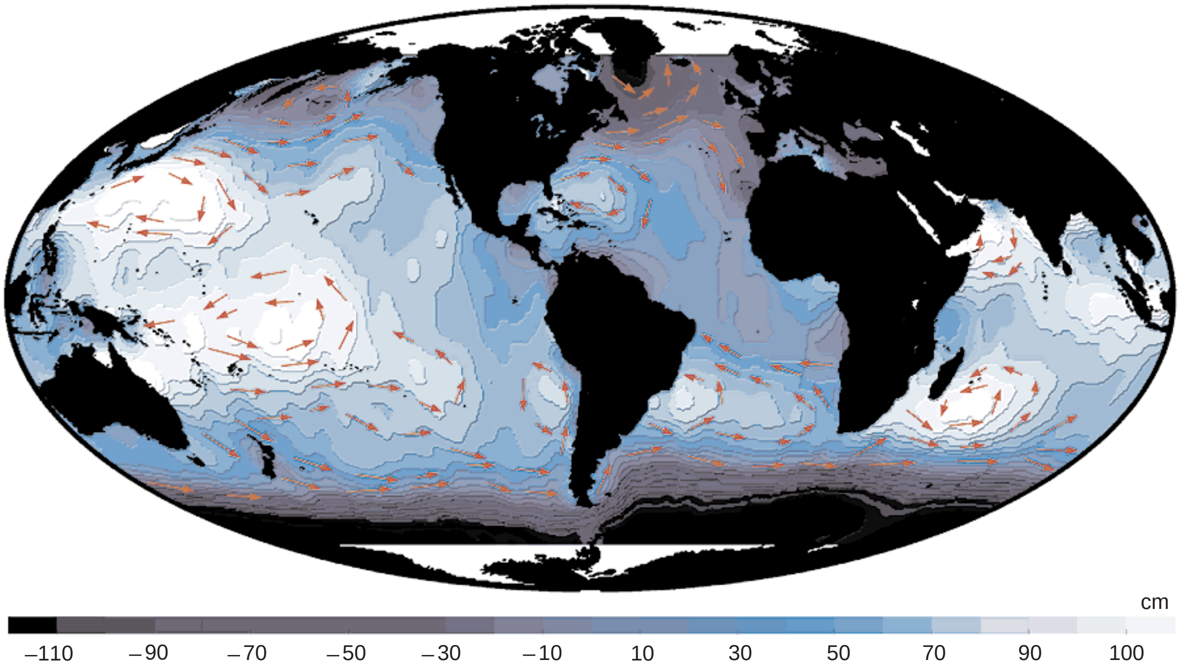

Figure 4 Surface geostrophic circulation determined from a combination of satellite altimetry and a model of the marine gravity field. (Courtesy of Space Oceanography Division, CLS, Toulouse, France.).

and Europe, will employ accelerometers, gravity gradiometers, and the Global Positioning System to virtually eliminate error in marine geoid models at spatial scales larger than 300 km and will thereby have a dramatic impact on physical oceanography. Not only will it be possible to accurately compute global maps of dynamic topography and geostrophic surface circulation, but the new gravity models will also allow recomputation of orbits for past altimetric satellites back to 1978, permitting studies of long, global sea level time-series. Furthermore, measurement of the change in gravity as a function of time will provide new information about the global hydrologic cycle and perhaps shed light on the factors contributing to global sea level rise. For example, how much of the rise is due simply to heating and how much to melting of glaciers? Together with complementary geophysical data, satellite gravity data represent a new frontier in studies of the Earth and its fluid envelope.

Sea Level Variability

At any given location in the ocean, sea level rises and falls over time owing to tides, variable geostrophic flow, wind stress, and changes in temperature and salinity. Of these, the tides have the largest signal amplitude, on the order of 1 m in mid-ocean. Satellite altimetry has enabled global tide models to be dramatically improved such that mid-ocean tides can now be predicted with an accuracy of a few cm (see **Tides**). In studying ocean dynamics, the contribution of the tides is usually removed using these models so that other dynamic ocean phenomena can be isolated.

The map in **Figure 5** shows the variability of global sea level for the period 1992–98. It is derived from three satellite altimeter data sets: ERS-1, T/P, and ERS-2 (ERS is the European Space Agency Remote Sensing Satellite), from which the tidal signal has been removed. The map is dominated by mesoscale (100–300 km) variability associated with the western boundary currents, where the rms variability can be as high as 30 cm. This is due to a combination of current meandering, eddies, and seasonal heating and cooling. Other bands of relative maxima (10–15 cm) can be seen in the tropics where interannual signals such as El Niño are the dominant contributor. The smallest variability is found in the eastern portions of the major ocean basins where values are < 5 cm rms.

To examine a sample of the sea level signal more closely, **Figure 6** shows the record from the region of the Galapagos Islands in the eastern equatorial Pacific. The plot includes two time-series: one from the T/P altimeter and the other from an island tide gauge, both averaged over monthly time periods. These independent records agree at the level of

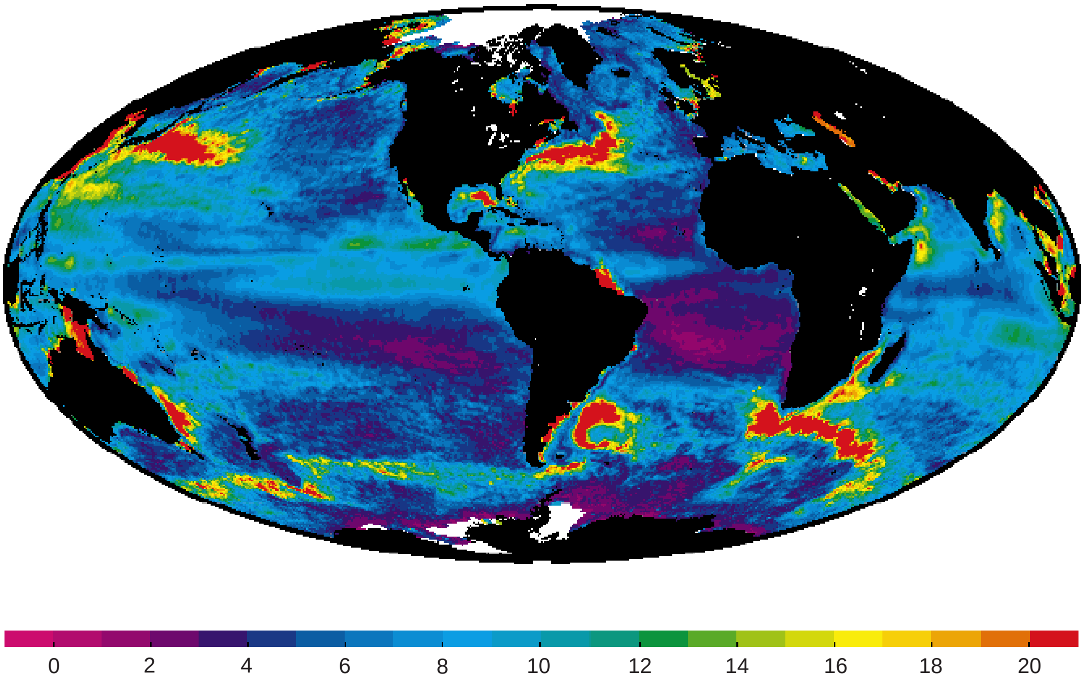

Figure 5 Variability of sea surface topography over the period 1992–98 from three satellite altimeters: Topex/Poseidon, ERS-1, and ERS-2. Highest values (cm) correspond to western boundary currents which meander and generate eddies. (Courtesy of Space Oceanography Division, CLS, Toulouse, France.).

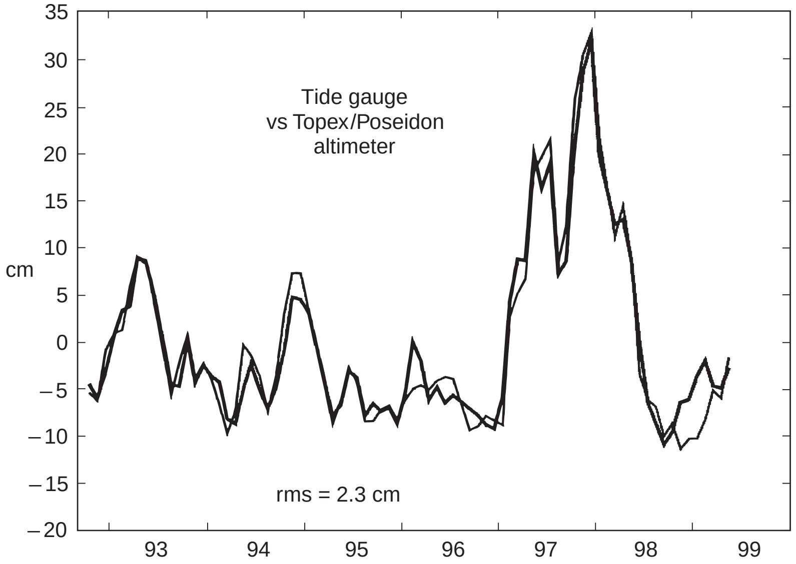

Figure 6 Monthly mean sea level deviation near the Galapagos Islands derived from tide gauge data and altimeter data. The ~ 2 cm agreement demonstrates the accuracy of altimetry for observing sea level variability. The effect of the 1997–98 El Niño is apparent.

2 cm, an indication of the remarkable reliability of satellite altimetry. The plot also illustrates changes associated with the El Niño event which took place during 1997–98. During El Niño, relaxation of the Pacific trade winds cause a dramatic redistribution of heat in the tropical oceans. In the eastern Pacific, sea level during this event rose to 30 cm above normal by December 1977 and fell by a corresponding amount in the far western Pacific. The global picture of sea level deviations observed by the T/P altimeter at this time is shown in **Figure 7**. Because sea level changes can be interpreted as changes in heat (and to a lesser extent, salinity) in the upper layers, altimetry provides important information for operational ocean models which are used for long-range El Niño forecasts (*see* **El Niño Southern Oscillation (ENSO)**).

Global Sea Level Rise

Tide gauge data collected over the last century indicate that global sea level is rising at about 1.8 mm y^{-1}. Unfortunately, because these data are relatively sparse and contain large interdecadal fluctuations, the observations must be averaged over 50–75 years in order to obtain a stable mean value. It is therefore not possible to say whether sea level rise is accelerating in response to recent global warming. Satellite altimeter data have the advantage of dense, global coverage and may offer new insights on the problem in a relatively short period of time. Based on T/P data collected since 1992, it is thought that 15 years of continuous altimeter measurements may be sufficient to obtain a reliable estimate of the current rate of sea level rise. This will require careful calibration of the end-to-end altimetric system, not to mention cross-calibration of a series of two or three missions (which typically last only 5 years). Furthermore, in order to interpret and fully understand the sea level observations, the various components of the global hydrologic system must be taken into account, for example, polar and glacial ice, ground water, fresh water stored in man-made reservoirs, and the total atmospheric water content. It is a complicated issue, but one which may yield to the increasingly sophisticated observational systems that are being brought to bear on the problem. For additional information, *see* **Sea Level Change**.

Wave Height and Wind Speed

In addition to sea surface topography, altimetry provides indirect measurements of ocean wave height and wind speed (but not wind direction). This is made possible by analysis of the shape and intensity of the reflected radar signal: a calm sea sends the signal back almost perfectly, like a flat mirror, whereas a rough sea scatters and deforms it. Wave height measurements are accurate to about 0.5 m or 10% of the significant wave height, whichever is larger. Wind speed can be measured with an accuracy of about 2 m s^{-1}. For additional information,

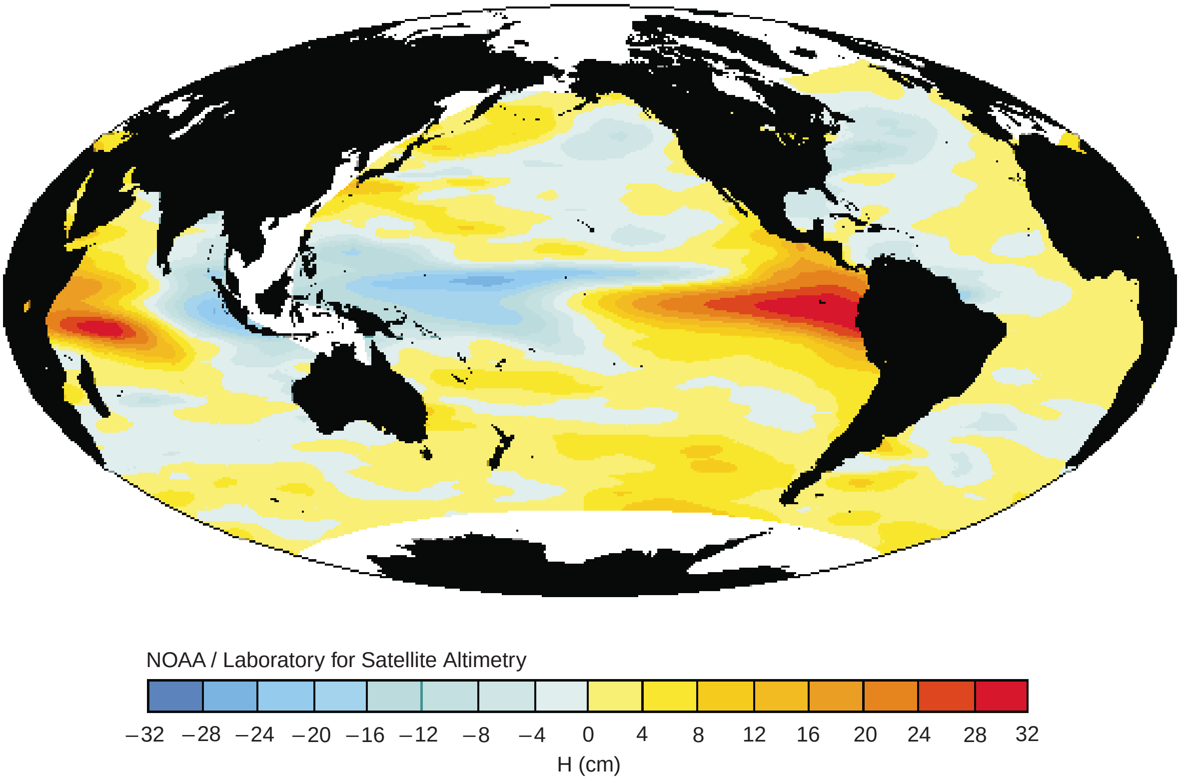

Figure 7 Global sea level anomaly observed by the Topex/Poseidon altimeter at the height of the 1997–98 El Niño. High (low) sea level corresponds to areas of positive (negative) heat anomaly in the ocean's upper layers.

see **Wave Generation by Wind** and **Surface, Gravity and Capillary Waves.**

Conclusions

Satellite altimetry is somewhat unique among ocean remote sensing techniques because it provides much more than surface observations. By measuring sea surface topography and its change in time, altimeters provide information on the Earth's gravity field, the shape and structure of the ocean bottom, the integrated heat and salt content of the ocean, and geostrophic ocean currents. Much progress has been made in the development of operational ocean applications, and altimeter data are now routinely assimilated in near-real-time to help forecast El Niño, monitor coastal circulation, and predict hurricane intensity. Although past missions have been flown largely for research purposes, altimetry is rapidly moving into the operational domain and will become a routine component of international satellite systems during the twenty-first century.

See also

Elemental Distribution: Overview. El Niño Southern Oscillation (ENSO). El Niño Southern Oscillation (ENSO) Models. Heat Transport and Climate. Satellite Oceanography, History and Introductory Concepts. Satellite Remote Sensing Microwave Scatterometers. Satellite Remote Sensing SAR. Upper Ocean Time and Space Variability. Wind Driven Circulation.

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