SATELLITE ALTIMETRY AND THE NOAA/NESDIS SEA-SURFACE HEIGHT SCIENCE TEAM[1]

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With the advent of satellite radar altimeters in the 1970s, the shape of the global ocean surface could be observed directly for the first time. What the data revealed came as a surprise 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 of meters. Marine geodesists and geophysicists knew that the oceans must conform to these shapes owing to spatial variations in the pull of gravity caused by seafloor topography. But for the oceanographic community, the concept of sea level and its variations in space and time were forever changed.

Today, satellite altimetry is used routinely by oceanographers who understand that sea surface topography contains a rich spectrum of information. In addition to mapping the deep ocean floor, altimeters enable observation of ocean currents and eddies, refinement of tide models, monitoring of El Nino, improvement in hurricane forecasts, and measurement of global sea-level rise. The NOAA/NESDIS Sea-Surface Height (SSH) science team has been emphasizing the transition from research to operations, both in terms of data processing and ocean applications. Here we show how SSH team activities in four sample areas – bathymetry, surface currents, global sea-level rise, and altimeter data sets - reflect the changing nature of satellite oceanography at NOAA.

Measurement Method

In concept, radar altimetry is among the simplest of remote sensing techniques. Two basic geometric measurements are involved. In the first one, 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).

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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 cm must be achieved to properly observe and describe the various oceanographic and geophysical phenomena of interest. Radar altimeters operate at two different frequencies simultaneously to correct for the ionospheric path delay, while a downward-looking microwave radiometer provides measurements of the integrated water vapor content which must also be known. Meteorological models are used to estimate the delay of the radar pulse by the atmosphere. Other models correct for biases created by ocean waves. Various tracking systems such as lasers, the Global Positioning System, and the "DORIS" Doppler system determine the satellite orbit to within 2 cm in the radial direction. The net result of all these measurements is a set of global sea-level observations with an absolute accuracy of ~3 cm at intervals of about 6 km along the satellite track. The altimeter footprint is exceedingly small–only a few km--so regional maps or "images" can only be derived by averaging data collected over weeks or more.

Gravity and Bottom Topography

Sea surface topography associated with spatial variations in marine gravity and bathymetry has vertical amplitudes 100 times larger than sea-level changes generated by tides and ocean currents. To first order, satellite altimeters therefore map the deep ocean floor. Using altimeter data collected by several different satellites over a period of years, it is possible to create global maps of sea surface topography having 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 3-dimensional images of the ocean floor–as if all the water were drained away (Fig. 1). 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 has been able to take advantage of new fishing grounds over previously uncharted seamounts.

Surface Currents

As a project of the National Oceanographic Partnership Program, the SSH team is working with other investigators on a project called OSCAR: Ocean Surface Current Analysis, Real-time. OSCAR is a pilot processing system being developed to provide operational ocean surface velocity fields computed from sea surface height and vector wind data in the tropical Pacific (Fig 2a). The OSCAR geographic coverage will be expanded to other basins and mid latitudes in the future. Methods to derive surface currents are the outcome of several years of research by Gary Lagerloef (Earth & Space Research) and Gary Mitchum (University of South Florida). The pilot project will transition that capability to NOAA for operational oceanographic applications.

Surface currents consist of a geostrophic component, which can be computed from the altimeter heights, and a wind-driven component, computed from wind vectors derived from satellite scatterometers. OSCAR is based on a hybrid geostrophic-Ekman scheme that is continuous across the equatorial latitudes. This model provides several improvements to an earlier scheme, including the treatment of vertical shear and the equatorial singularity, that yield much better comparisons with mooring and drifter data in the eastern Pacific cold tongue. OSCAR velocity maps are updated on a weekly basis, with an eventual goal of 2-3 day maximum delay from the time of satellite measurement. Grid resolution is 100 km for the basin scale. Finer resolution fields will be evaluated in the vicinity of certain Pacific island regions. Data applications include large-scale climate diagnostics and prediction, fisheries management and recruitment, monitoring debris drift, larvae drift, oil spills, fronts, and eddies. Additional uses for search and rescue, naval and maritime operations will be investigated.

These velocity fields have been particularly useful in monitoring the evolution of El Nino conditions. We find from the historical analysis in the Pacific that equatorial surface velocity anomalies lead sea surface temperature anomalies by about three months. Between November 2002 and January 2003, OSCAR analyses (Fig. 2b) showed a rapid change from eastward to westward current anomalies. Three months later, sea surface temperature anomalies followed suit, changing from warm to cold and indicating a switch from El Nino to La Nina conditions. The OSCAR analyses are provided routinely to the NOAA National Centers for Environmental Prediction where they are used to monitor the continued evolution of surface currents and the relation to sea-surface temperature. In addition to this monitoring activity, NOAA is using the satellite-derived current estimates to verify model currents and diagnose model errors.

Another immediate application of these data relates to fisheries management and marine wildlife research in the region. Movements of several species of sea turtle in the tropical Pacific are being tracked by satellite with System Argos. Results compiled by Jeff Polovina of NOAA National Marine Fisheries Service show that some turtle tracks follow meandering portions of the North Equatorial Current and North Equatorial Counter Current. The surface current data allow researchers to examine the oceanography of the habitat these turtles are using, for example, and evaluate to what extent they are using the equatorial currents and regions of surface convergence. Findings indicate that different species/stocks use different habitats. Some forage at or near the surface at convergences and others forage sub-surface away from currents.

Global Sea-Level Rise

Tide gauge data collected over the last century indicate that global sea level is rising at about 1.8 mm per year. 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 difficult to say whether sea-level rise is accelerating today. Satellite altimeter data have the advantage of dense, global coverage and are beginning to offer, in a relatively short period of time, new insights on the global sea level problem. TOPEX/Poseidon and Jason-1 altimeter data collected since 1992 indicate that global sea level is rising at about 2.8 mm per year. The significance of this result should become more clear as the record becomes longer (it is thought that 15-20 years of continuous altimeter measurements may be needed to obtain a stable value for the current rate).

In order to interpret and understand these 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. Laury Miller of the SSH team has recently worked with Bruce Douglas of Florida International University on a simple study that sheds light on the dominant source of sea-level rise during the 20th century. By examining both tide gauge data and deep measurements of temperature and salinity for several ocean regions, they conclude that ocean warming accounts for only about one-third of the sea-level rise over the last century. An example of their work is shown in Figure 3 . This Eastern Pacific region is bounded by tide gauges at Honolulu, San Francisco, San Diego, and Balboa, Panama. All four gauge records show sea-level trends of ~2 mm per year during the 20th century, despite the fact that the gauge sites are widely separated and, thus, subject to different vertical land motions and local hydrographic conditions. However, the ~19,000 hydrographic stations from the ocean interior show that only ~0.5 mm per year of sea-level rise can be accounted for by changes in temperature and salinity. One conclusion is, therefore, that melting of continental ice sheets and glaciers must be dominating the rise of sea level by simply increasing the ocean mass. It is a complicated issue, but one which is yielding to the increasingly sophisticated observational systems that are being brought to bear on the problem.

Altimeter Data Sets

The altimetry state of the art has been changing rapidly over the last years, with new and improved orbits and corrections constantly being generated. While this is certainly good news, it creates a dilemma for users, who must keep their data sets accurate and up to date. In response to this problem, a multi-satellite data base is currently under development at NOAA. Access is provided through pre-compiled programs or custom-made tools based on a versatile package of Fortran subroutines. The interface with the data base is extremely configurable, such that each user can create a highly customized data stream based on individual preferences of data rejection, area, data content, and applied corrections.

In order to avoid inconsistencies between the different altimeters, all model corrections are provided homogeneously throughout the missions. The data base allows repeated upgrades to any data field, without impact to the user interface. It is up to the user to pick one of the various competing corrections provided.

The value of combining altimeter data in a homogeneous way, adding the strengths of the different missions and compensating their weaknesses, is worth the trouble of meticulously sorting out the various data products. For mapping mesoscale ocean features, the increased spatial resolution provided by multiple altimeter satellites is an obvious advantage. But even for making estimates of global sea-level rise over the last decade and projections into the future, it may be best to combine data from all altimeter satellites. One reason is that sea-level rise may be perceived differently by different altimeters because of aliasing. For example, the TOPEX/Poseidon mission is considered to be state-of-the-art and yields a global sea-level rise of 2.4 mm per year over the period 1993-2003. But as shown in Fig. 4, a number of other satellite altimeters also collected data during this time. We will therefore continue to refine these data sets to extract the maximum possible accuracy.

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. Altimeter data are now routinely processed in near-real time to help forecast El Nino, 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 21st century.

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Figure Captions

Fig. 1. Global ocean bottom topography derived from satellite altimeter data together with shipboard observations of depth. An interactive, web-based version of this map is available at http://ibis.grdl.noaa.gov/bathy

Fig. 2. (a) Web site for OSCAR: Ocean Surface Current Analysis, Real-time. (http://www.oscar.noaa.gov) (b) OSCAR surface current anomaly fields in the equatorial Pacific that show the abrupt change from El Nino conditions in November 2002 (top panel) to La Nina in January 2003 (bottom panel).

Fig. 3. The rate of sea-level change in the eastern Pacific from 4 tide gauge records (purple) compared to ~19,000 hydrographic stations (green), where temperature and salinity were used to derive sea level using a 5-year running means (red). Whereas the tide gauges yield a rate of 2 mm per year, only 0.5 mm per year is accounted for by changes in temperature and salinity, suggesting input of water to the ocean from melting continental ice.

Fig. 4. Global sea-level rise has been observed over 12 years by 6 different satellite altimeters. TOPEX/Poseidon, the most accurate of these missions, yields a rate of 2.4 mm/yr over 1993-2003.

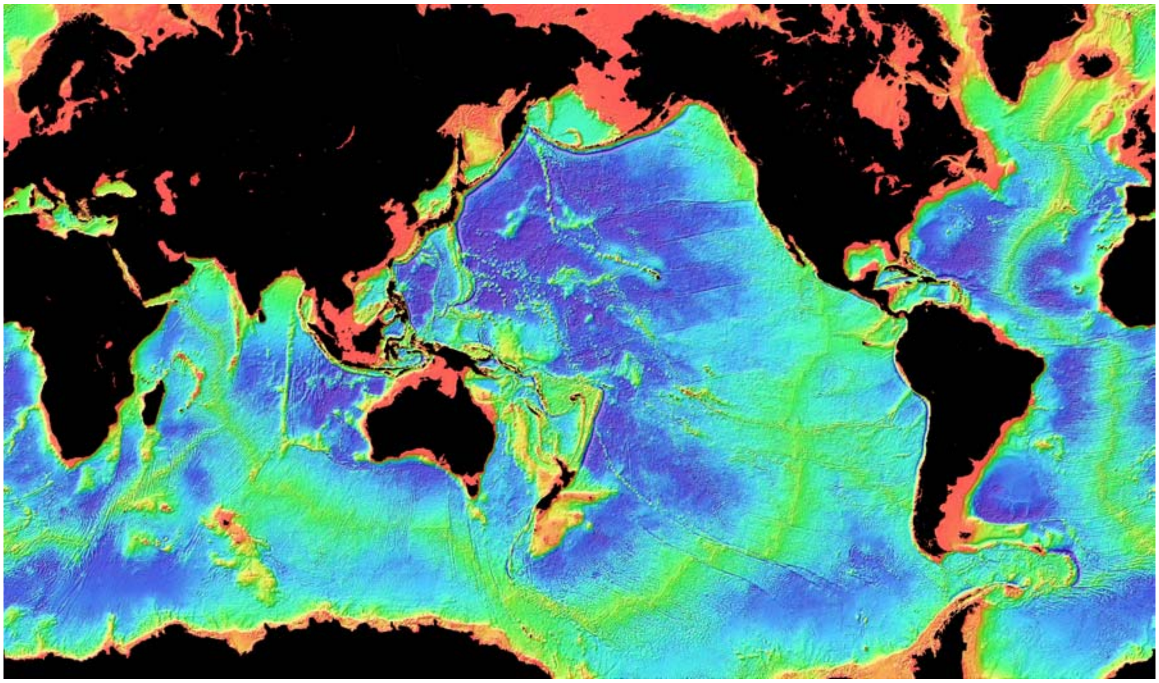
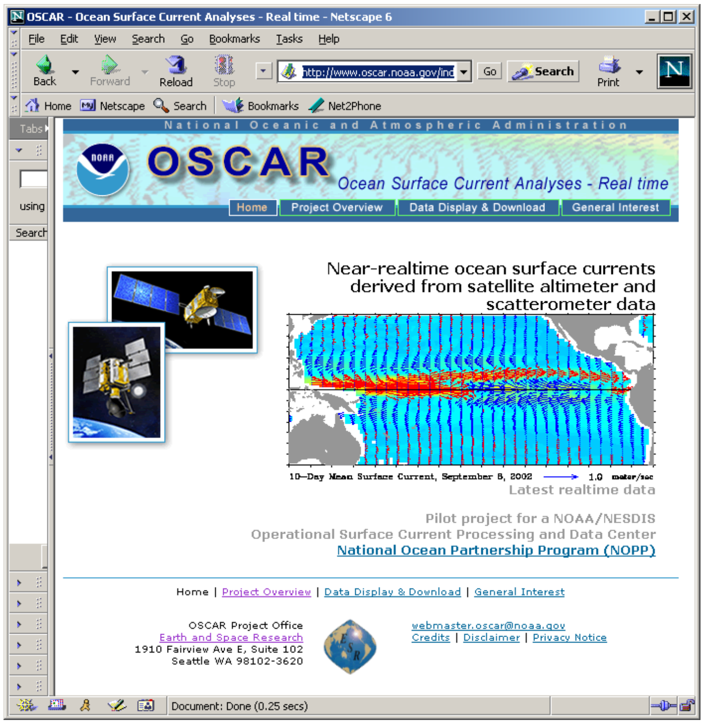


Fig. 1

Fig 2



Near-realtime ocean surface currents derived from satellite altimeter and scatterometer data

Latest realtime data

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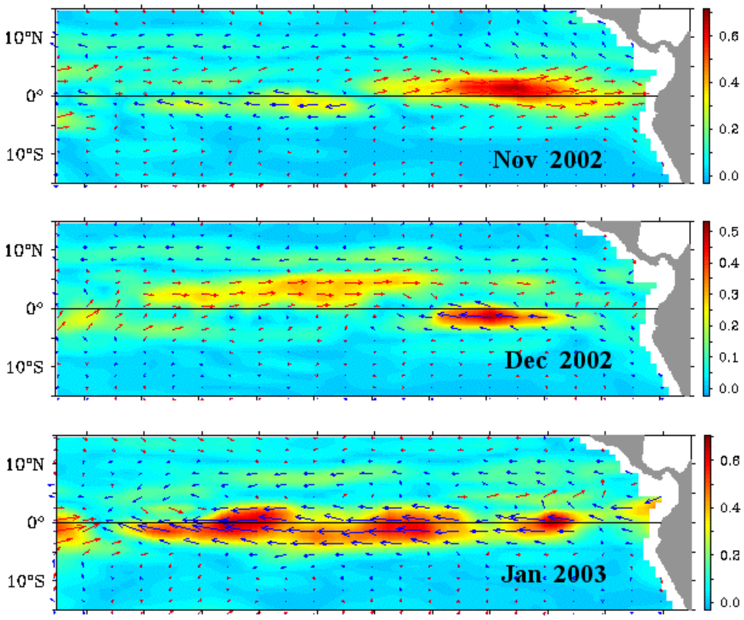

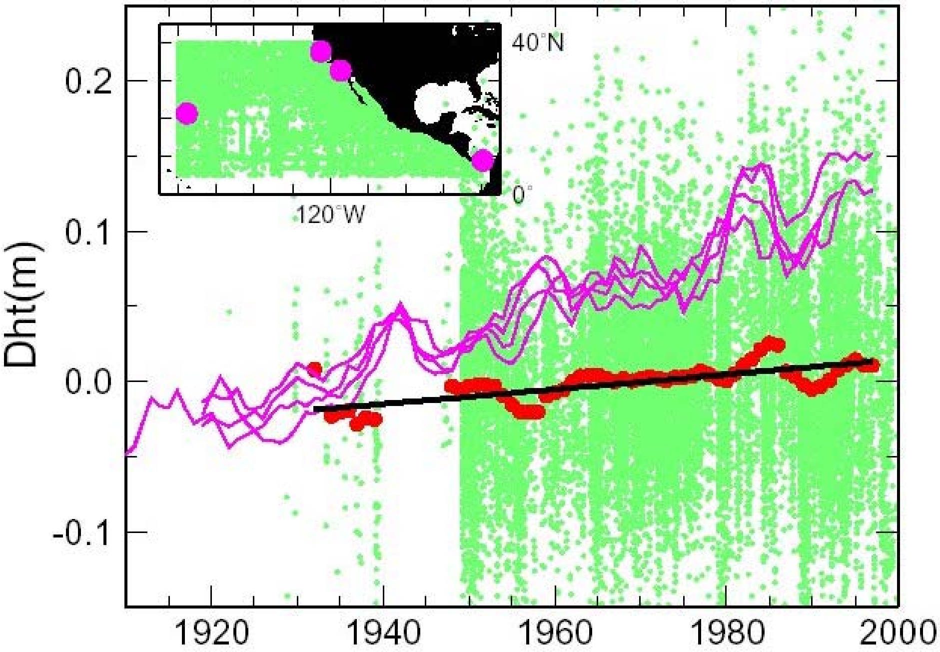

Fig 3

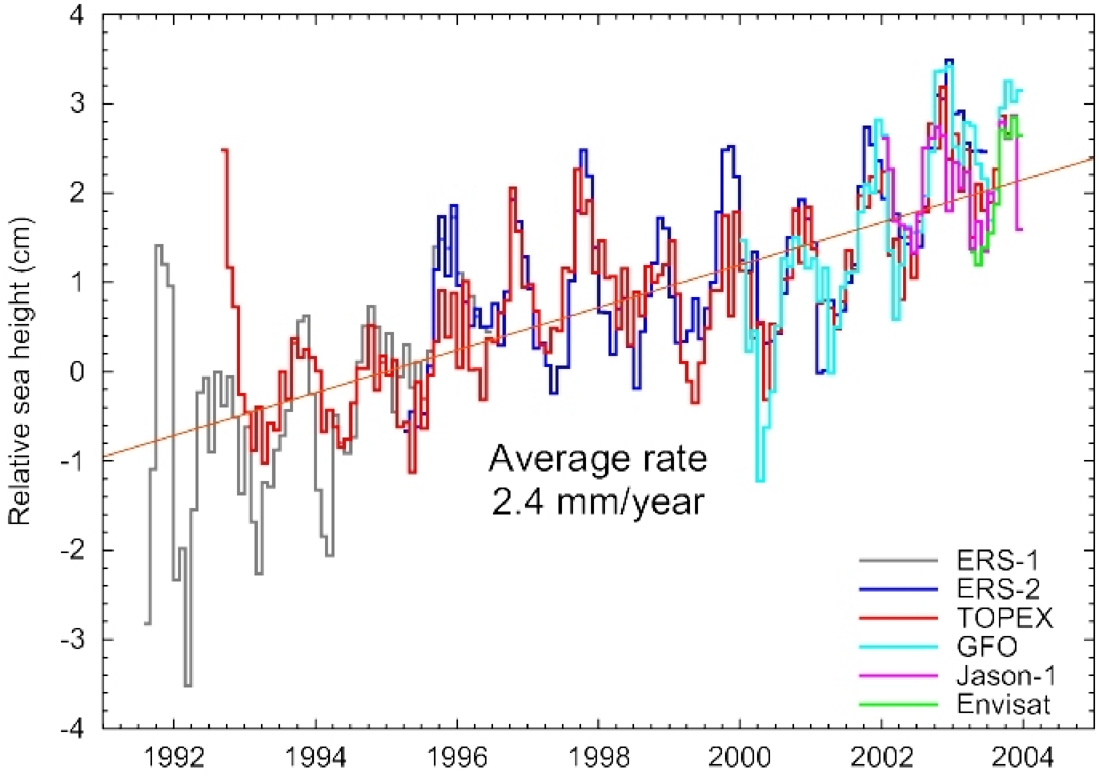
Relative sea height (cm)
4
3
2
1
0
-1
-2
-3
-4
1992
1994
1996
1998
2000
2002
2004
Average rate
2.4 mm/year
ERS-1
ERS-2
TOPEX
GFO
Jason-1
Envisat

Fig. 4