Advances in Large-Scale Ocean Dynamics From a Decade of Satellite Altimetric Measurement of Ocean Surface Topography

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ABSTRACT

The past decade has seen the most intensive observations of the global ocean surface topography from satellite altimeters. The Joint U.S./France TOPEX/Poseidon (T/P) Mission has become the longest radar mission ever flown in space, providing the most accurate measurements for the study of ocean dynamics since October, 1992. The European Space Agency's ERS-1 and –2 Mission also provided altimetric observations from 1991-2000. The combined data from T/P and ERS have higher spatial resolution and greater coverage than the individual missions. Major advances in large-scale ocean dynamics from these observations are reviewed in the paper, including the ocean general circulation and its variability, the evolution of the El Niño Southern Oscillation cycles as well as the emerging decadal variability, the response of the ocean to wind forcing, assimilation of altimeter data by ocean general circulation models and the estimation of deep ocean circulation, global sea level rise, and tidal models and mixing.

Keywords: satellite altimetry, ocean circulation, TOPEX/Poseidon, El Niño, tides

1. INTRODUCTION

The utility of a spaceborne radar altimeter for the study of ocean circulation and dynamics was first demonstrated by Seasat (Fu , 1983). Despite the short 3-month duration of the satellite mission, a wealth of dynamic phenomena in the ocean was revealed in the observations, including tides, eddies, and boundary currents. Following Seasat, the U.S.Navy launched Geosat in 1985. With capabilities similar to Seasat, Geosat collected 4 years' worth of data and generated a wide range of applications in the study of global ocean dynamics (Fu and Cheney, 1995). While the results from Seasat and Geosat were tantalizing, the limitations caused by the rather large measurement errors were disappointing. For example, the uncertainty in determining the satellite's orbits creates an error in ocean surface topography on the order of 1 meter over a scale of thousands of kilometers. The errors caused by the lack of accurate measurement of the tropospheric water vapor content lead to topography errors about 10 cm over a scale of a few hundred kilometers. There are important oceanographic signals at all these scales, dictating a better measurement system for making substantial progress in ocean dynamics.

The Joint American/French TOPEX/Poseidon Mission (T/P hereafter) was the first altimetric mission optimally designed for the study of the dynamics of ocean circulation. The mission concept was developed in the early 1980s. Realizing the outstanding problem in orbit determination, NASA and CNES initiated a 10-year effort to improve the modeling of the earth's gravity field as part of the mission. To make precise tracking of the satellite's positions, the satellite carries three tracking systems: laser retroreflectors, DORIS receivers, and GPS receivers. The altimeter was the first with dual frequencies (13.6 and 5.3 GHz) for removing the path delays caused by the ionopsheric free electrons. Also carried was a 3-frequency microwave radiometer (18,21, 37 GHz) for removing the path delays caused by the water vapor in the atmosphere. The satellite's orbit configuration was dictated by optimal performance in orbit determination and tidal sampling. The reader is referred to Chelton et al. (2001) for a description of the principle of radar altimetry and to Fu et al. (1994) for the details of the T/P satellite and instruments.

T/P was launched in 1992 and has provided 10 years' worth of high-quality data so far. Displayed in Figure 1 is the comparison of the sea level measurements made by T/P and a tide gauge at the Christmas Island in the equatorial Pacific Ocean. Note that the rms differences are close to 2 cm. During the past decade, ESA also

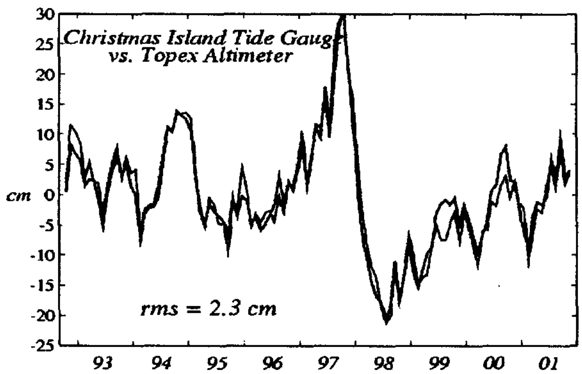

Fig. 1 Monthly sea level anomalies from T/P (black) and a tide gauge (blue) at the Christmas Island.

launched ERS-1 and ERS-2 satellites, both of which carried radar altimeters. Although the ERS altimeter performance is not as good as T/P, the data from the two ERS altimeters have provided spatial coverage to complement the T/P observations. The unprecedented continuous 10-year observation of the global ocean topography has revolutionized the way we study the global oceans. Significant advances have been made in a wide range of subjects in ocean dynamics. This paper presents a summary of the highlights from this remarkable progress.

2. OCEAN GENERAL CIRCULATION

Satellite altimetry provides a unique approach to the determination of the ocean dynamic topography. The difference between the height of sea surface measured by altimetry and the height of the geoid is the ocean dynamic topography from which the surface geostrophic velocity is then determined. The top panel of Figure 2 shows the dynamic topography derived from Geosat (Nerem et al. 1990), to be compared with

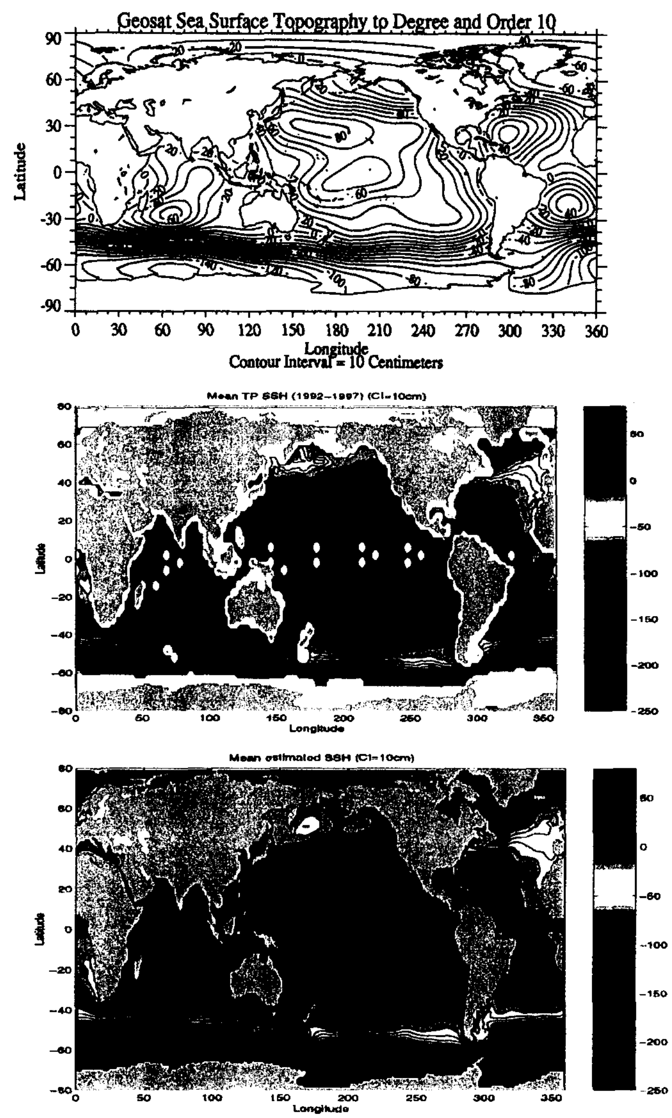

Fig. 2 Top: surface dynamic topography from the Geosat data (Nerem et al., 1990. Middle: from the T/P data (Stammer et al., 2000). Lower: from a numerical model assimilating the T/P data (Stammer et al., 2000)

the middle panel showing the result from T/P, and the lower panel showing the computation from an ocean model that assimilates the T/P data (Stammer et al., 2000). The improvement of T/P over Geosat is quite substantial. However, the spatial resolution is limited by the errors in the present geoid models that amount to 10 cm at 1000 km scales. The newly launched GRACE satellite is expected to provide better geoid models that will have only 1 cm error at 300 km scales. Note that the model has provided a smoother estimate of the topography that has no voids due to lack of observations. Constrained by the surface observations, the numerical models also make estimates of the circulation of the deep ocean, as shown in Figure 3 for a depth of 2000 m (Tong Lee, personal communication, 2002). Such constrained model estimates allow the determination of the flux of mass, heat, and dissolved greenhouse gases in the ocean as well as the air-sea fluxes.

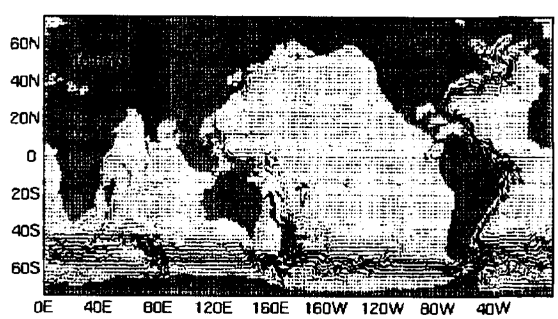

Fig. 3 Current velocity vectors at 2000 m estimated from a numerical model assimilating the T/P data.

3. MESOSCALE VARIABILITY

What satellite alimetry has done best to date is to illustrate how the global oceans are changing with time. Shown in Figure 4 is a map of the standard deviation of ocean topography computed using data from T/P, ERS-1 and ERS-2 (Ducet et al., 2000). The standard deviation is dominated by the mesoscale fluctuation of ocean currents and eddies. The map reveals the details of the mesoscale ocean variability not seen before. Of particular interest is the structure around the Grand Banks, resembling the path of the North Atlantic Current. This feature was incorrectly mapped from previous observations. The new

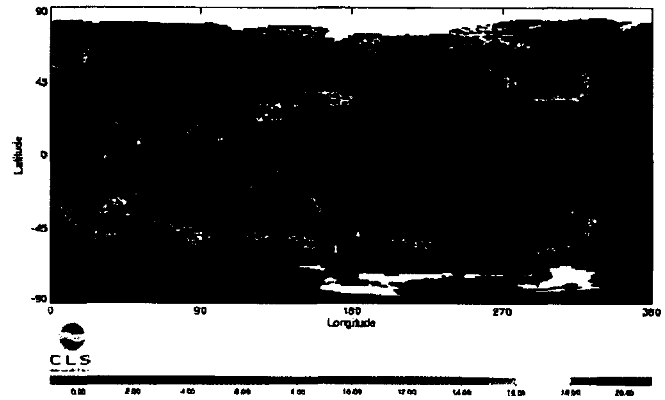

Fig. 4 Standard deviation of the ocean surface topography (in cm) computed from the data from T/P, ERS-1 and –2 (Ducet et al. 2000)

finding has motivated the improvement in the spatial resolution of numerical ocean models to as fine as 1/16 degree for resolving the details of ocean dynamics.

4. EL NINO AND LA NINA

The much improved orbit determination for T/P has enabled the best global observations of the large-scale ocean variability. The global view of the 1997-98 El Niño as it evolved in real time was the best demonstration of this powerful new capability. For the first time, altimetry observations were used by the US NOAA climate prediction models for improving forecast skills. Shown in Figure 5 are the yearly averaged sea surface anomalies for 1997-2000, depicting the evolution of El Niño into La Nina, followed by the development of a slow change in the Pacific, possibly a new phase of the Pacific Decadal Oscillation.

5. GLOBAL MEAN SEA LEVEL RISE

After averaging over the entire globe, the errors in the T/P observations are mostly cancelled out due to their random nature. The errors in the computation of the global mean sea level change are generally less than 5 mm over a 10-day span (Nerem and Mitchum, 2001), allowing a credible estimate for the slow change of the global mean sea level. Figure 6 shows the comparison between the estimates from T/P and in-situ temperature observations (Cabanes et al., 2001).

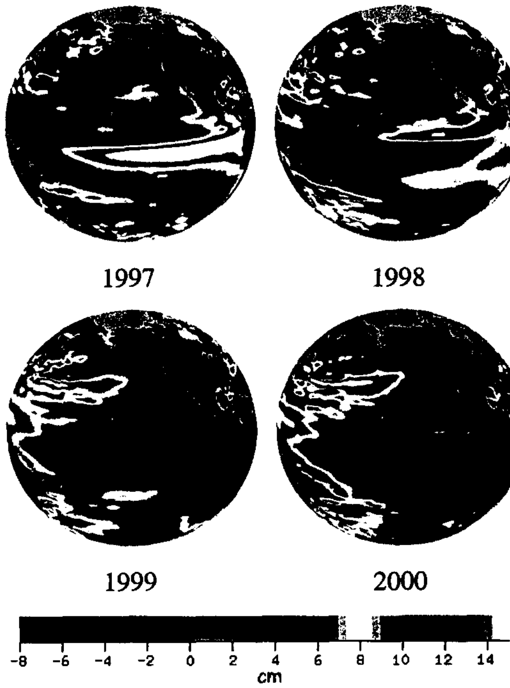

Fig. 5 Yearly averaged surface topography anomalies computed from the T/P data from 1997-2000.

The 2.7 mm/year rise estimated from T/P is largely consistent with the thermal expansion of the global oceans over a period of eight years.

6. TIDES AND TIDAL MIXING

Ocean topography changes on the order of 1 meter due to the tides. If not corrected for, the tidal signals would overwhelm most other oceanographic signals. Specifically designed for sampling ocean tides with the satellite orbit's inclination of 66 degrees, T/P observations have led to the development of the best ocean tide models. The accuracy of such models is better than 3 cm in an rms sense globally. The energy fluxes derived from these models revealed an unexpected finding: close to 30 % of the tidal dissipation occurs in the deep ocean (Egbert and Ray, 2001), in contrast to the old notion that most of the tidal energy dissipates over the shallow seas. Such deep ocean dissipation (Figure 7) is via the conversion of external tides into internal tides over ocean bottom topographic features. The tidal dissipation provides a powerful source of mixing in the deep ocean and is important to

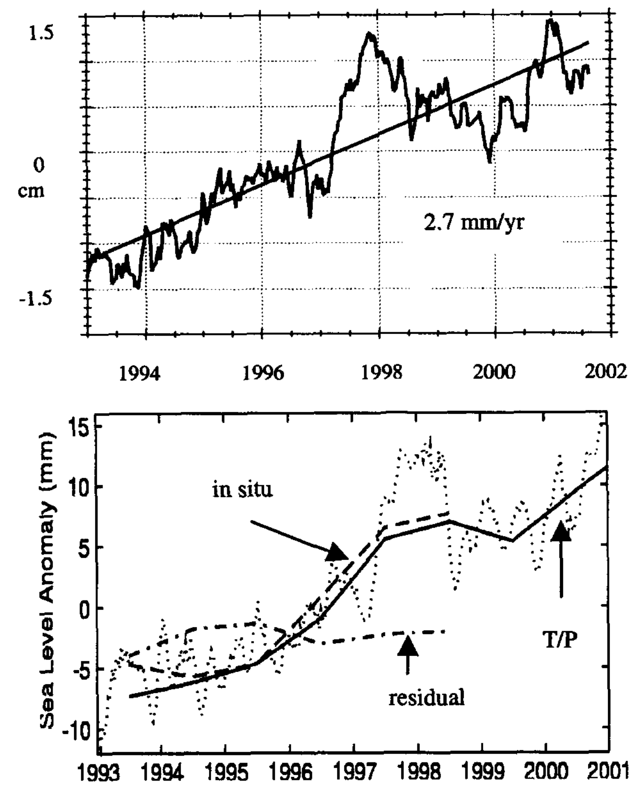

Fig. 6 Top: Global mean sea level in cm determined from T/P (Nerem et al., 2001). Lower: Global mean sea level from T/P (dotted), after being smoothed (solid), from estimation based on in-situ temperature data (dashed), and the residuals (dash-dotted, T/P – in situ).

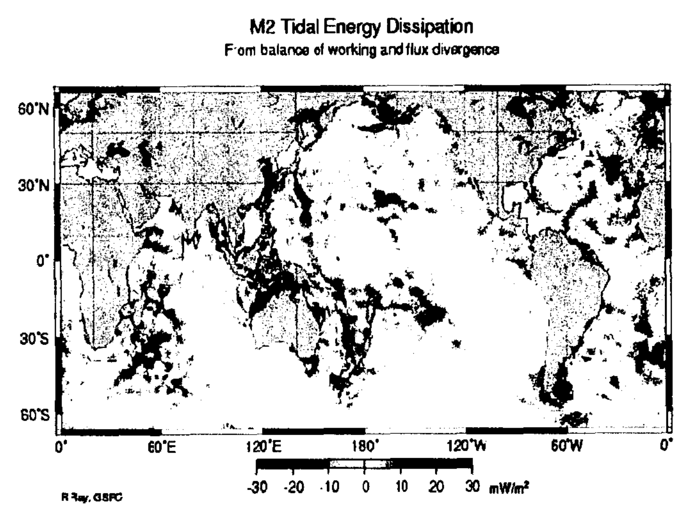

Fig. 7 M_2 dissipation rate (in mW/m^2) derived from a tide model constructed from the T/P data (Egbert and Ray, 2001).

the understanding of the formation of the thermocline and ocean general circulation. This new finding has triggered a series of efforts of including tidal mixing in ocean models.

7. CONCLUSIONS AND OUTLOOK

The decade-long altimetric observations of the global ocean surface topography have revolutionized the way we study the ocean. Never before has a dynamic variable of the global oceans been monitored routinely over such a long period of time. This capability has broken new ground for routine estimate of the physical state of the ocean. The success of ocean altimetry has provided a key motivation for the Global Ocean Data Assimilation Experiment. The paradigm of oceanography has shifted from exploration to quantification, a crucial step towards the ability to make climate prediction. The challenge in the future is the sustenance of this important data stream.

The follow-on to T/P, called Jason-1, was launched on December 7, 2001. This mission has the same payload and flies in the same orbit as T/P. During the first eight months of the Jason-1 mission, T/P and Jason-1 fly over the same ground tracks separated in time by only 60 seconds. Comparisons of the two measurements taken under nearly identical sea conditions are extremely useful in the calibration and validation of Jason-1 in an effort to make its measurements consistent with those of T/P for building a long time series record from the two satellites. After the completion of this Calibration Phase, T/P is planned to be moved to a new orbit that will produce ground tracks interleaving those of Jason-1 (i.e., the old T/P tracks). In this Tandem Mission, the two satellites will be able to sample the global ocean with twice the spatial resolution and improve the knowledge of the global mesoscale variability as well as coastal tides.

ESA launched ENVISAT in March, 2002. Its payload includes a dual-frequency altimeter and a dual-frequency microwave radiometer for water-vapor corrections. Flown in the same sun-synchronous orbit (in which the solar tides are aliased to the mean topography) as ERS-1 and ERS-2, ENVISAT altimeter data will complement Jason-1 in a similar manner as ERS-1 and 2 did to T/P. Additionally, the U.S. Navy's Geosat Follow-on (launched in 1998) has also been producing useful data along the Geosat ground tracks.

In the long run, satellite altimetry should be part of an operational global ocean observing system run by operational agencies such as the U.S. NOAA and others. Before this goal becomes a reality, a bridging mission currently called Ocean Surface Topography Mission (OSTM) is being planned for launch in 2006 to continue the precision altimetry data stream towards 2010. OSTM is a collaborative effort among NASA, CNES, NOAA and EUMETSAT. It represents the transition of satellite altimetry from a research/development mission to an operational mission that will be conducted indefinitely in the future. As an experimental payload being considered for OSTM, a wide-swath ocean altimeter has been designed for measuring ocean topography over a swath of 200 km in width at a resolution of 15 km x 15 km, covering nearly 100% of the global ocean surface between +/- 66 degree latitudes every 10 days. This new instrument will be able to resolve the Rossby radius of deformation at all latitudes and go a long way towards understanding and monitoring of eddies, fronts, and boundary currents that have not been properly sampled by conventional altimeters.

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