A New Milestone in Large-Scale Ocean Dynamics: The First Three Years of the TOPEX/POSEIDON Mission

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The US/France TOPEX/POSEIDON (abbreviated as T/P hereafter) satellite, which has been in orbit since August, 1992, is the first global ocean observing system specifically designed for studying ocean dynamics. The satellite uses a state-of-the-art radar altimeter system to determine the sea surface topography - the height of sea surface relative to a reference ellipsoid- with an unprecedented accuracy, and has returned a wealth of new information on the ocean circulation and its variations. The difference between the sea surface elevation (after removing the effects of tides and atmospheric loading) and the geoid (the equi-geopotential surface) defines the ocean dynamic topography which is the surface pressure field associated with ocean currents. The observation covers the global oceans from 66° S to 66° N every 10 days, allowing oceanographers to monitor the dynamic state of the global ocean on a routine basis. For the first time, the ocean is being sampled with sufficient spatial and temporal resolution to address its variability at frequencies and wavenumbers previously inaccessible by in-situ observations.

Additionally, the observation has also been used to study ocean tides as well as geodesy and geophysics. The radar altimeter also measures wind speed and wave height, which are part of the mission's data product in addition to sea surface topography. Most of the results from the mission to date have been published in two special issues of the Journal of Geophysical Research (Vol. 99, No. C12, 1994; Vol. 100, No. C12, 1995). Summarized in this paper are highlights from what we have learned about the large-scale ocean dynamics from this unique data set. We would like to emphasize, though, that this paper is not intended to be a comprehensive review, but to provide a sampler of recent work to keep the science community updated on the progress of and opportunities from the mission.

Large-Scale Variabilities

The frequency-wavenumber spectrum of global ocean variability is a crucial piece of information for understanding ocean dynamics. An estimate of such a spectrum, the first based on real data, was made by Wunsch and Stammer (1 995). A major characteristic of the spectrum is a ridge of variance at the annual period for wavelengths ranging from 500 to 10,000 km. Appreciable energy levels are revealed at shorter periods as well. The spatial pattern of the annual cycle was studied by many investigators. A hemispheric asymmetry in the amplitude is observed (e.g., Cheney et rd., 1994). The mean sea level annual variation in the northern hemisphere is larger than that in the southern hemisphere by a factor of two. Such asymmetry, which is largely consistent with the seasonal changes of oceanic heat content that is larger in the northern hemisphere, was not detectable by other satellite altimeters due to large orbit errors. This new observation imposes a useful constraint on estimation of the global air-sea heat exchange.

The large-scale variability at intraseasonal time scales (periods shorter than 180 days) has been difficult to study using in-situ data due to inadequate spatial sampling in the presence of the ubiquitous mesoscale eddies. T/P observation revealed for the first time the geographic distribution of the intraseasonal large-sale variability and its barotropic (depth independent) nature as a forced response to wind (Chao and Fu, 1995). At lower frequencies, the large-scale variability exhibits predominantly westward phase propagation, a characteristic of Rossby waves. The phase speeds of these waves were found to be systematically higher than theoretical predictions based on standard theory (Chelton and Schlax, 1996). These higher speeds, up to three times faster than the theoretical prediction at high latitudes, indicate that the response of high latitude ocean to tropical events such as El Niño is much faster than previously believed. In the Antarctic Circumpolar Current, evidence of eastward propagation due to the effect of mean flow on Rossby waves was reported for the first time (Hughes, 1995).

There are many new findings of the energetic of ocean currents. Qiu (1995) examined the relationship between the eddy kinetic energy and the absolute current field in the Kuroshio Extension region and reported a linear increase of the eddy energy south of the Kuroshio Extension as a result of conversion of mean flow kinetic energy via instability. White and Heywood (1995) demonstrated that the eddy kinetic energy in the North Atlantic Current region is related to the migration of the current in relation to the interannual variations of the wind stress curl field. The unprecedented accuracy of T/P data has led D. Stammer of MIT to the discovery of a universal wavenumber spectrum for the mesoscale variability, specified by latitude, energy level, and vertical stratification of water.

The T/P observation has provided the first test bed for high-resolution computer simulations (e.g., Semtner, 1995). The overall geographic patterns of sea level variability, the seasonal cycle, as well as ml-time large-scale sea level variations are in reasonable agreement; their discrepancies are indicative of possible missing physical processes in the model. The sea level variance produced by the model is generally less than the observation by a factor of two or more. The discrepancy is most pronounced in the eddy-rich regions. The causes and consequences of the discrepancy remain obscure. Comparison of along-track wave-number spectra indicates that the model might need even higher spatial resolution to fully resolve the mesoscale eddies. Assimilation of the T/P data into models has shown improvements in the simulation of the mean flow, the eddy kinetic energy distribution, as well as subsurface current field (e.g., Blayo et al., 1994).

Tropical Dynamics

With its launch in August 1992, T/P has covered more than half of the prolonged anomalous warming of 1991-95, which mostly involved the Tropical Pacific Ocean and to some extent, the Indian Ocean. As for the Tropical Atlantic Ocean, anomalous high sea level associated with a warm event was observed in 1995, A combination of T/P and in-situ observations has allowed comprehensive studies of these events.

With the vanishing of the Coriolis force toward the equator, very accurate sea level is needed in the equatorial regions in order to derive correct surface geostrophic currents. Given the numerous corrections involved in measuring sea level from space, in situ validation is a fundamental step prior to any use of altimetry data. The anticipated 2-3 cm accuracy of T/P altimeter data for the detection of large-scale sea level has been verified with the use of the Tropical Ocean Global Atmosphere (TOGA) sea level and TOGA-TAO Pacific networks (e.g., Cheney et al., 1994), as well as two TOGA-TAO moorings specially outfitted with additional temperature, salinity, and pressure sensors to measure within 1 cm the dynamic height from the surface to the bottom directly beneath two T/P crossovers (Picaut et al., 1995). Comprehensive tests of estimating geostrophic currents from T/P data have also been conducted. Many successful comparisons were made to direct current observatsions from the TOGA-TAO moorings and drifting buoys.

Analysis of the space-time structure of the T/P sea level estimates together with the TOGA-TAO observations indicates that sea level variability in the Pacific equatorial band was primarily due to equatorial Kelvin and Rossby wave activities associated with the prolonged sequence of El Niño events in the past three years (e.g., Busalacchi et al., 1994). These waves and their reflection at the oceanic boundaries are believed to be important mechanisms for the formation and decay of El Niño. Observations of such mechanisms are difficult using in-situ methods. Boulanger and Menkes (1995) did not find any evidence of Rossby wave reflection at the western boundary to terminate the 1992-93 warm event as theory would suggest, However, a recent study of J-P. Boulanger and L-L. Fu has shown evidence for the reflection of first-mode downwelling Rossby waves into downwelling Kelvin waves from January to July 1994. This wave reflection mechanism may have played a role in the onset of the 1994-95 boreal winter warm event.

The throughflow from the Pacific to the Indian Ocean has been suggested to be an important factor in determine the El Niño Southern Oscillation cycle. R. Lukas of University of Hawaii and collaborators have developed indices of the throughflow using T/P sea surface height differences between the western equatorial Pacific and the eastern Indian Ocean. The comparison with the Davao-Darwin sea level index indicates that T/P data are better in determining the seasonal cycle of the throughflow as well as its weakening during El Niño.

Using T/P data, S. Arnault of ORSTOM-Paris and Y. Menard of Centre National d'Etudes Spatiales (CNES) have detected a strong warm event in the Tropical Atlantic beginning in early 1995. The sea surface height anomalies in the Gulf of Guinea began to rise as early as January 1995, reaching more than 5 cm compared to the 1993-94 mean sea surface height anomalies. This description from altimetry data is in excellent agreement with sea surface temperature and wind data analysis.

Ocean General Circulation

A basic motivation for satellite altimetry is to provide ocean dynamic topography and, therefore, a reference surface geostrophic velocity for determining the general circulation at all depths. Initial estimates of this surface using T/P data at a horizontal resolution of about 1000 km (Nerem et al., 1994) are estimated to have a total error greater than 10 cm rms within 30” of the equator, but smaller errors (<10 cm rms) poleward of 30° latitude. Inaccuracies in the geoid are the dominant source of error in these computations. Even with these apparently large errors, T/P has provided new information about the ocean general circulation as discussed below.

Since the launch of T/P there has been a major effort to improve the geoid model for the Earth. A variety of new models have been completed over the past few years by the University of Texas at Austin, NASA Goddard Space Flight Center (GSFC), and CNES. The global cumulative standard errors of the state-of-the-m models are now about 5 cm rms for a resolution of 1400 km. At higher resolution the geoid errors become larger than the magnitude of the dynamic topography, rendering the atimetric estimates unreliable. At the resolution of 1400 km, errors in upper ocean geostrophic currents outside of ±1 0° latitude are estimated to be 2 cm/sec rms.

Preliminary comparisons between the T/P dynamic topography and surface dynamic height relative to a deep reference level (>2000 m) from the recently completed Pacific survey of the World Ocean Circulation Experiment Hydrographic Program have verified the formal error assessments discussed above. The discrepancy points out isolated regional problems in the geoid that need to be corrected for T/P to resolve the subtropical gyres at these scales. However, the T/P data have already resolved the subtropical and subpolar gyres in the south Indian Ocean much better than historical hydrographic data (Park and Gamberoni, 1995).

Over the past three decades numerical general circulation models of the ocean have improved dramatically with the increase in computational power (Semtner, 1995). These models can now provide realistic simulations of most of the basic features of the general circulation. The T/P data, because of their global coverage and accuracy, have revealed strengths and weaknesses of the models. The nns difference in surface dynamic height between a two year mean from the Los Alamos Parallel Ocean Program model and a two year mean from T/P at scales larger than 1000 km is 14 cm. Given the 10 cm error estimate for the geoid, this implies that the model error is about 10 cm as well at these scales. However the geoid errors are smaller at larger scales and become less than the errors of model simulations as well as estimates from hydrography at scales larger than about 2500 km (R. Rapp, personal communication). The T/P results have thus provided new information on the ocean circulation at the scales of the ocean basins,

A collaboration between the U.S. Defense Mapping Agency and GSFC is underway to improve the Earth's gravity model through a reprocessing of the unclassified data base, in addition to some recently released classified gravity data. This effort may improve the geoid accuracy in ocean regions at scales greater than 14(M) km and refine the surface topography of the ocean gyms from T/P data. However, at this resolution, the more dramatic features of the geoid over trenches, sea mounts, and ridges, as well as the strong ocean currents near western boundaries and the circumpolar current, are not resolved Only an independent satellite mission to measure the gravitational field will provide the necessary increase in geoid accuracy and resolution to significantly enhance the use of T/I? data for general circulation research.

Mean Sea Level Variation

The remarkable accuracy and precision of T/P data indicates that the evolution of the mean sea level and its geographical distribution may be observed by this system, but this goal remains extremely challenging in terms of accuracy, especially due to the systematic errors in the various components of the measurement system. Existing estimates based on

3 years of T/P data indicate a global mean sea level rise at a rate of 4-6 mm/year (e.g., Nerem, 1995). A correction for altimeter instrument drift, about 2.8 mm/year for the TOPEX altimeter, has been applied to these estimates. A number of independent calibration experiments indicate an additional drift at a rate of about 2 mm/year existing in the sea level measurement, resulting in a revised sea level rise of 2-4 mm/year. However, the cause for this additional drift is not understood yet.

The lower bound of the estimated value, 2 mm/year, is fairly close to the rate of sea level rise estimated from tide gauge data since the beginning of the century, but these data also suggest large variations of sea level rise with time. However, the apparent sea level rise is not spread homogeneously over the ocean. The map in Figure 1 (based on data provided by S. Nerem, see Nerem (1995)) shows the rate of a linear sea level change estimated from a least-square fit of a linear term plus the annual and semi-annual harmonics to the first 3 years' worth of T/P data (cycles 1-108). Due to the relatively short duration of the record, the linear trends are dominated by the interannual variability of the ocean. For instance, the large sea level rise in the western Pacific was related to the strengthening of the westward trade winds in 1994 preceding the 1994-95 El Niño event. The similar sea level rise in the western Indian Ocean was also related to an increase in the trade winds in the Indian ocean during the same period of time. The sea level rise north of Hawaii is believed to be related to the passing of a low-frequency Rossby wave. These sea level changes of interannual time scales make it impossible using the current data set to detect long-term sea level rise caused by possible global warming, and underscores the need for acquiring a multi-decadal, multi-mission time series of altimeter data of T/P quality.

The patterns of sea level change shown in Figure 1 are similar to those of the third empirical orthogonal mode of the sea level signals (Hendricks et al., 1996). This mode would be the first EOF mode when the annual and semi-annual harmonics are subtracted. This mode of sea level change is coherent in space and time with the sea surface temperature (SST) signal, which was rising at a globally averaged rate of 0.07 °C/year during 1993-1994 (Nerem, 1995). This would suggest that the sea level signal is related to heat storage. Taking the higher rate of sea level rise at 4-6 mm/year, the sea level to SST drift ratio is 6-9 cm/°C. Given typical values of the seawater thermal expansion coefficient and assuming that the SST drift signal is correlated with the temperature evolution below the surface, this ratio typically requires a temperature change over a layer 300450 m thick. This seems large as the time scale of these observed variations is short compared to the time scale needed for heat invasion in such a layer. Of course, SST is not necessarily a good indicator of subsurface signals, especially in the tropics. However, taking the lower bound of the estimated sea level rise at 2 mm/year, one would only need to heat a layer of 150 m, which is more realistic. The correlation between sea level and SST signals is very encouraging and indicates that one is observing actual oceanographic interannual variations.

T/P data suggest that the seasonal variation of the mean sea level is very small. Yet, mean SST does show a seasonal signal of 0.5°C in amplitude, which should induce a seasonal steric height signal of the order of 5 mm amplitude (assuming an average mixed layer depth of 50 m). However, seasonal water mass transfer to the atmosphere (3 mm equivalent sea level amplitude) and to the continents could cancel this steric height effect. In fact, T/P data might provide useful information on the latter which is poorly known.

Concluding Remarks

T/P has established satellite altimetry as a global observing system for studying ocean dynamics. For the fiit time oceanographers are provided with continuous, well-sampled high-quality data of the sea level, a dynamic boundary condition for the ocean circulation. A host of new features of global ocean dynamics has been revealed by the observations, including the patterns of global seasonal cycle, frequency and wavenumber spectra, dynamics of Rossby waves and equatorial waves, gym-scale variabilities, ocean tides, as well as global mean sea level variations. These observations have provided a valuable test bed for ocean circulation theories and the ever maturing computer models of ocean general circulation. NASA has planned to operate the T/P satellite through at least 1998, providing up to 6 years' worth of data, Among many potentially fruitful applications of this growing data set, one would expect to see the development of an enterprise in which the data are used in conjunction with computer models for routine global ocean analysis and predictions. To make a real impact on understanding the global ocean change and its role in climate, global observing systems of the quality of T/P need to be maintained in the future. The dynamic boundary condition for ocean circulation provided by altimetry is crucial for a global climate observing system.

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Figure Caption

Figure 1. The linear trends of sea level change estimated from the observation made by the TOPEX/POSEIDON satellite during a 3-year period from September, 1992 to August, 1995,

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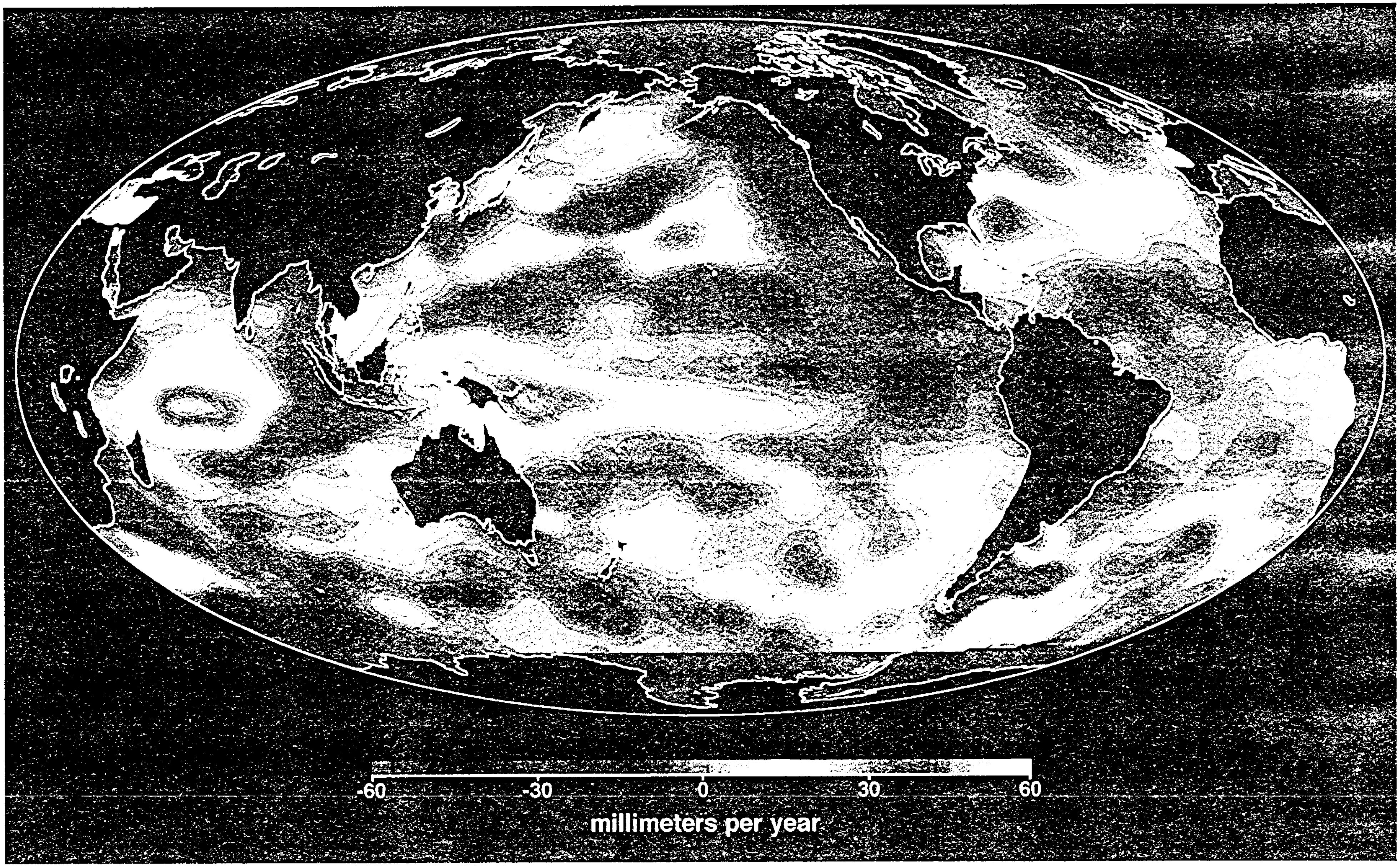
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