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Paper Session I-C - The Ocean and Climate: Results from the TOPEX/ POSEIDON Mission

Lee-Lueng Fu
Jet Propulsion Laboratory, California Institute of Technology

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Lee-Lueng Fu
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109

Introduction

The ocean circulation and its fluctuations are known to have important consequences for climate variations. It is believed that the relatively rapid swings of global temperatures (over 10 degree change in less than 30-50 years) in the past interglacial period is primarily associated with changes in the global ocean circulation which regulates the transport of water, beat, and carbon dioxide in the ocean and their exchange with the atmosphere. Unfortunately, most knowledge of the global circulation has been acquired through piecemeal observations of the temperature and salinity properties of the ocean and used under the radical assumption that the ocean circulation is essentially steady. It is known however, from direct observations of ocean currents, that the fluid flow is turbulent on an enormous range of spatial and temporal scales (ranging from about 30 to 10,000 km and days to hundreds and thousands of years).

As with any turbulent flow, understanding of the ocean circulation can only be obtained if the system is sampled and then described on all relevant scales. Because the ocean is a global phenomenon, but with major regional variations, any adequate observational system must itself be global. Attempts to forecast the ocean circulation so as to make inferences about future climate are thus dependent upon having adequate observations - a formidable requirement for such a large fluid system.

The only known practical approach to observing the global ocean with useful space and time resolution is from orbiting satellites. But because sea water is a good electrical conductor, spaceborne observations are restricted to the surface properties of the ocean, generally producing measurements of only limited use for making inferences about the full-three dimensional water column. There is only one observable from space that is directly linked to the circulation as a whole: the surface pressure field, manifested as the sea surface elevation.

If the ocean were at rest, the sea surface would coincide with a gravitational equipotential surface (the specific surface is designated the "geoid"). With the removal of such high frequency phenomena as tidal variations, the shape of the sea surface relative to the geoid is the oceanic "dynamic topography". Simple theory based upon the equations of fluid dynamics [1] shows that the dynamic topography is a manifestation of the movement of the entire oceanic water column, extending in some circumstances to the sea floor. Sufficiently accurate measurements of the sea surface thus provide very powerful constraints upon the large scale circulation and its variability [2].

Space measurements of the sea surface topography are based upon radar altimeters in a simple measurement geometry illustrated in Figure 1. The height of the sea surface relative to the Earth's center of mass is obtained by subtracting the altimeter range measurement from the geocentric altitude of the spacecraft (the radial orbit height). But the accuracies required to be useful are better than 10 cm, and achieving them requires solutions to a host of technical problems.

On August 10, 1992, the United State and France launched their joint TOPEX/POSEIDON (abbreviated as T/P hereafter) satellite for making altimetric observations of the sea surface [3]. This is the first satellite altimetry system specifically

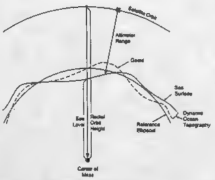

Fig. 1 The geometry of the technique of satellite altimetry

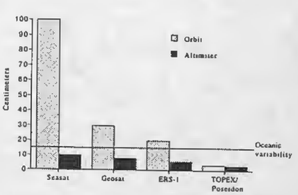

Fig. 2 The evolution of the measurement accuracy of various satellite altimeters. The horizontal line denotes a representative sea level change (15 cm) caused by the variations of large-scale ocean currents.

designed for studying the circulation of the global oceans. The spacecraft is operating in an orbit which repeats its underlying ground-track every 10 days. Results to date show that the mission is producing observations of the global sea surface elevation with an unprecedented accuracy of 5 cm everywhere, and much better in some places. This precise knowledge of the shape of the sea surface is directly related to the dynamical processes governing ocean currents throughout the entire water column and provides oceanographers with the first true global observation system. Designed for a lifetime of 3-5 years, the satellite is providing the ability to describe and understand the dynamics of ocean circulation and its time variability with sampling adequate to understand its climatic consequences.

The Mission

The primary instrument of the T/P mission is a US-provided dual-frequency radar altimeter. The measurements are made at two frequencies (5.3 GHz and 13.6 GHz) and are combined to obtain precise altimeter range measurements that are free from errors caused by the ionospheric free electron content. A French-built single-frequency (13.6 GHz) solid-state radar altimeter is an experimental sensor to demonstrate low-power, low-weight altimetry technology for the future. The two altimeters share the same antenna with the American altimeter operating for approximately 90 % of the time and the French altimeter for the remainder. A three-frequency (18, 21, and 37 GHz) microwave radiometer, is used to make corrections for variations in the speed of microwave propagation caused by variations in the water vapor content of the troposphere. The 21-GHz channel is the primary channel and the 18-GHz and 37-GHz channels are used to remove the effects of wind and cloud cover, respectively.

Three separate tracking systems are used to determine the positions of the satellite and to determine any altimeter instrument bias. A laser retroreflector array is used with a network of Satellite Laser Ranging stations. The spacecraft is in view of a laser tracking station about 6-10% of the time. A second system called Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) is based on microwave Doppler techniques and is composed of an onboard receiver and a network of ground transmitting stations. These stations, equipped with meteorological sensors (measuring temperature, humidity and atmospheric pressure) for correcting for atmospheric effects on the transmitted signals, provide a quasi-continuous tracking of the satellite (80% of the time).

The DORIS signals are transmitted at two frequencies (401.25 and 2036.25 MHz) to allow the removal of the effects of the ionospheric free electrons in the tracking data.

A third tracking system uses the Global Positioning System (GPS). A GPS receiver on the satellite receives signals from the network of the GPS satellites and provides precise, continuous tracking of spacecraft by using the technique of differential ranging. The continuous tracking has made possible highly accurate orbit determination with much-reduced need for prior gravity-field estimation and orbit trajectory equations.

The T/P satellite is an adaptation of the Multi-Mission Modular Spacecraft which was modified to meet the T/P requirements. The satellite was launched on 10 August 1992 by an Ariane-4 rocket from the European Space Agency's launch site at Kourou, French Guiana. The satellite began collecting science data 42 days after the launch - following a period of testing, calibration and maneuver. The final operational orbit has an altitude of 1336 km, an inclination of 66 degrees, and a repeat period of 10 days. The ground tracks below the orbit are maintained within 1 km from their nominal positions by occasional orbit maneuvers. The orbit configuration was determined by the requirements of precision orbit determination, the sampling of ocean tides (an error for studying ocean circulation) as well as ocean current variabilities.

The top priority during the first 6 months of the mission was to test and calibrate the overall system. Numerous field campaigns were conducted by the mission project and science teams, including occupation of two dedicated sites at Point Conception, California and at Lampedusa Island in the Mediterranean Sea. In the meantime, the satellite laser ranging and DORIS data were used to test the orbit determination procedures and to modify the prior gravity field model to optimize its performance for the mission. The results of this "verification phase" are reported elsewhere [4]. The primary conclusions are that both the altimeter measurement and the orbit determination have exceeded pre- launch requirements. The root-mean-square errors in both measurements are in the range 3-4 cm, resulting in an uncertainty in the range of 4-5 cm (primarily random error) for the sea level measurement. Shown in Figure 2 is a comparison of the performance of T/P with three other recent satellite altimeters. Only T/P has sufficient accuracy for detecting the large-scale oceanic signals. The accuracy of the T/P sea level measurement has been illustrated by numerous comparisons to observations of tide gauges [5]. The calibrated mission data are now available without restriction to all users [6] on magnetic tapes and CD-ROMs within two months from data reception. "Quick-look" data are available via electronic media to operational users within seven days from reception.

Science Capabilities

A major goal of the mission is to determine the global absolute surface geostrophic circulation - a long-pursued goal of physical oceanographers. However, this determination depends not only on precise altimetry measurement, but also on precise knowledge of the geoid. The long-wavelength component of the geoid has been greatly improved by the T/P mission in its effort of achieving the unprecedented orbit determination performance. Up to spherical harmonics degree and order 20 (wavelengths greater than 2000 km), the commission error of an interim T/P geoid model, called the Joint Gravity Model-2 (JGM-2), is about 13 cm. The detailed knowledge of the short-scale geoid still awaits a dedicated space gravity mission. Shown in Figure 3 is the time-averaged dynamic topography based on the first year's T/P data and the JGM-2 geoid. This is the first direct observation of the shape of the global sea surface due to ocean currents. The average was performed on snap shots of the ocean available every 10 days, as opposed to the climatological information about the ocean gathered by ships in the past by putting together observations separated by

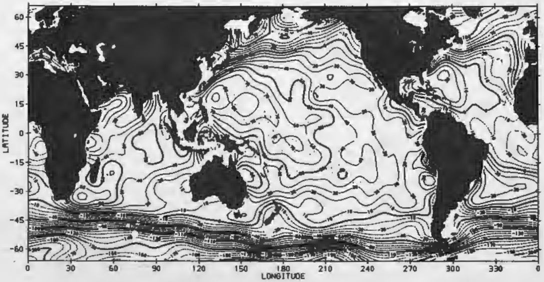

Figure 3. Time-averaged ocean dynamic topography based on the T/P data from the first year of the mission and the JGM-2 geoid. Spherical harmonics up to degree and order 20 are used to construct the map. Contour interval is 10 cm with dashed lines denoting negative values. Thick solid lines mark every fifth contour line.

years and decades. The true averaged picture of a turbulent flow has to be obtained by averaging over time intervals shorter than the time scales of the variabilities.

As noted above, ocean topography is a measure of sea level relative to the Earth's geoid, a surface on which the gravity field is uniform. Oceanographers use ocean topography maps to calculate the speed and direction of ocean currents the same way meteorologists use maps of atmospheric pressure to calculate the speed and direction of winds. T/P is the first space mission that allows scientists to map ocean topography with sufficient accuracy to study the large-scale current systems of the world's oceans. The total relief of ocean topography shown in this map is about two meters. The maximum elevation is located in the western Pacific Ocean and the minimum is around Antarctica. In the Northern Hemisphere, ocean currents flow clockwise around the highs of ocean topography and counterclockwise around the lows. This process is reversed in the southern hemisphere. The major current systems of the world's oceans such as Kuroshio (the current south of Japan), Gulf Stream, and the Antarctic Circumpolar Current, among others, are clearly visible in the map. These highs and lows are the oceanic counterparts of atmospheric circulation systems. The existence and basic structure of these ocean systems are constant, but the details of these systems are constantly changing. Therefore, these features can be considered the "climate" of the ocean. Through the enormous amount of heat transported by the large-scale circulation systems revealed by the map, the ocean plays a fundamental role in maintaining the current habitable climate on Earth. Understanding the dynamics of ocean circulation and its role in climate change is the main goal of the T/P Mission.

The ocean circulation is changing on all space and time scales, ranging from weeks to decades and longer. Because the satellite's ground tracks are repeating precisely (within a 2-km band) every 10 days, the temporal variations of sea level are mapped with high degree of accuracy with little effects of the geoid uncertainties. Both seasonal and interannual variations of the sea level resulting from the ocean circulation and its interaction with the atmosphere have emerged from the 2.5 years of data collected to date. An important interannual change in the ocean is the phenomenon of El Nino and Southern Oscillation (ENSO), involving a eastward shift of the huge pool of warm water in the western tropical Pacific (the warmest of the World Ocean) as a result of weakened trade winds. Recurring irregularly every 3 to 7 years, ENSO normally brings worldwide anomalous weather patterns, ranging from droughts in Australia to floods in the gulf states of the United States. The damage of the 1982-83 ENSO, the strongest of the century, amounts to $ 9 billions.

The tropical Pacific has slipped into an unusually long sequences of ENSO since 1991, with three out of the past four winters being characterized as in an ENSO condition. Two of them were detected by T/P: the events of 1992-93 and 1994-95. Shown in Figure 4 are the sea level anomalies along the equator in the Pacific as a function of time since the beginning of the mission. Light shades are higher sea levels (relative to the 1993 average) and darker shades are lower sea levels. The ENSO event is normally preceded by an eastward-propagating wave of higher sea levels called a Kelvin wave, manifested on the figure by a sloping (upward from left to right) band of light shades. One can clearly note that there are two such incidents, the first one from October 1992 to May 1993 and the second one from September 1994 to January 1995. These waves were triggered by weakened trade winds, which would normally pile up warm water against the western boundary of the tropical Pacific. When the trade winds become weaker than usual, the excess warm water begins sloshing eastward and creates a Kelvin wave.

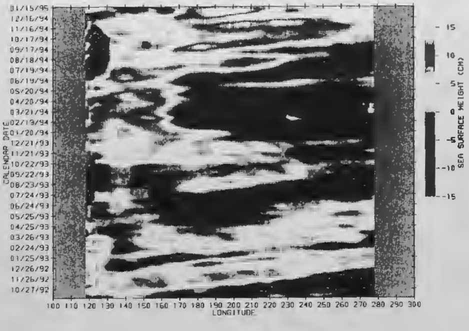

Figure 4. Sea level anomalies along the equator in the Pacific Ocean. Longitudes in degree East.

The positive sea level anomalies are directly related to the excess amount of upper ocean warm water, which in turn allows the determination of the excess heat associated with the ENSO, a key piece of information for the determination of the strength of an ENSO and its temporal evolution. For the first time, T/P provides this information with a high degree of accuracy on a routine and global basis (Figure 5). It is anticipated that this flow of information will make significant improvement in the forecast of future ENSO events.

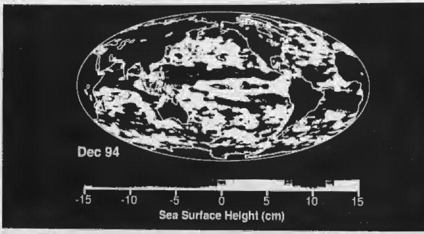

Figure 5. Monthly averaged sea level anomalies for December, 1994. The white region in the central equatorial Pacific is associated with the 1994-95 El Nino.

An important, unexpected application of the T/P data is the monitoring of the variation of the global mean sea level, a benefit of the unprecedented measurement accuracy. The variation of the mean sea level is a robust indicator for global warming or cooling because it is a cumulative measure of the effect. This information has been obtained from the tide gauges sparsely distributed worldwide. Because of its uneven distribution, the tide gauge database is prone to sampling errors. Moreover, the reference to the Earth's crust is also problematic for determining the absolute sea level. The ability of reliably determining a trend of sea level rise provides an early warning not only for possible global warming but also for a potential coastal hazard effecting a large population over the world. Preliminary analysis of the T/P data suggests that the measurement system may be accurate enough to provide a capability of monitoring the millimeter per year variation. Displayed in Figure 6 is the short-term trend based on the T/P data, showing a rise at a rate of 2.9 +/- 0.9 mm/year (courtesy of S. Nerem of NASA Goddard Space Flight Center). Although this trend is consistent with the record of the mean sea surface temperature [7], the record is still too short to be conclusive regarding both its accuracy and the significance of the trend detected. The global mean sea surface temperature record of the past 10 years does show 3-5 year short-term variations apparently unrelated to a long-term trend.

Finally, T/P is also serving as an extremely accurate global tide gauge, providing the most accurate determination of the open ocean tides. The observation is also useful for determining the Earth's gravity field which have important consequences for geodesy and geophysics. The reader is refer to a special section of the results from T/P in the Journal of Geophysical Research (Vol. 99, No. C12, 1994).

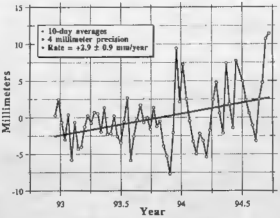

Figure 6. Global mean sea level variations from TOPEX/POSEIDON altimeter data.

(courtesy of S. Nerem of NASA Goddard Space flight Center)

Perspectives

The launch of T/P was coordinated with an international oceanographic campaign called the World Ocean Circulation Experiment (WOCE), directed at understanding the role of the circulation in climate. Much of the WOCE field program is coincident in time with T/P, permitting mutual intercalibration, and the ability to combine in situ and space observations for best-estimates of the circulation and its variability. Indeed, T/P was envisioned as a central element in WOCE.

Much of the rationale for the T/P mission arose from the conclusion that the only way oceanographers would be able to understand the ocean circulation, and its role in climate, was to combine dynamical models of the circulation with observations adequate to constrain and test those models. For example, the dominant influence of the ocean on climate involves its transport of heat and freshwater, and the uptake, expulsion and transport of carbon dioxide among many other properties. Ocean general circulation models are rapidly reaching a state of development [8] in which they can incorporate much of the known physics (and ultimately, chemistry and biology) of the ocean circulation. T/P provides the first accurate global observations of the ocean circulation to validate the rapidly maturing global ocean models. Close agreement of the observation with the state-of-the-art ocean model [9] suggests that one can begin combining the data with models to achieve a near-optimal estimation of the state of the ocean and its time evolution. These data will be subject of intense study for many years. Just as with atmospheric models, which must be "updated" several times per day with direct observations of the atmosphere, oceanic models require combination with global observations to render them realistic representations of the actual ocean. The science plan for T/P anticipates the combination of the altimetric and other data with general circulation models, which are then employed to compute the climatologically important property fluxes. Actually doing so is an important and difficult problem in estimation theory ("assimilation" in meteorology jargon) which will be one of the central activities of the T/P team and the wider oceanographic community in the next several years.

Concluding Remarks

TOPEX/POSEIDON is providing the field of physical oceanography with the first truly global ocean observing system: producing a "snap shot" of the global ocean circulation every 10 days. Coupling with two other concurrent developments - WOCE and the maturing technology of global ocean modeling, T/P is creating opportunities for making significant advancement in the understanding of global ocean dynamics and its relation to climate.

But climate is by definition a long-term problem. To achieve the ultimate WOCE goal of understanding the ocean's role in climate, the global observations provided by T/P must be sustained, with consistent quality, for many years - beyond the present anticipated mission lifetime of five years. A series of follow-on missions to extend the T/P data stream to the indefinite future is being studied jointly by the US and French governments. A positive outcome may prove crucial if we are ever to understand the climate system.

Acknowledgments

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