# IDENTIFICATION OF EL NIÑO SIGNALS WITH SATELLITE ALTIMETRY

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## ABSTRACT

El Niño warming in the equatorial Pacific causes a distinctive change in both local and global sea level, which can be measured quite accurately with space-borne satellite altimeters such as TOPEX/POSEIDON. The sea level changes are reflective of changes in the internal density structure of the ocean due to variations in the ocean heat storage and mass. Because the anomalous warming tends to begin significantly below the ocean's surface, altimetry can detect El Niño signals weeks to months before surface temperature measurements detect them. An example of this is tracking strong Kelvin waves across the Pacific several months before the peak of El Niño warming. Although the altimeter data alone cannot differentiate between changes in ocean heat storage and mass, by combining altimetry with other data and output from numerical models, one can begin to study how changes in the ocean mass influence the Earth's rotation. These signals are examined during the El Niño event of 1997.

## INTRODUCTION

Until the last several decades, the El Niño phenomenon was considered a localized interannual variation in the waters of the eastern Pacific, with a frequency of 3 to 7 years. Villagers along the Pacific coast in Peru and Ecuador had known about the intermittent warming of the ocean for centuries. Recent studies, however, have shown that the phenomenon extends across the equatorial Pacific and is coupled with the atmosphere, and that El Niño in the Pacific can effect weather patterns in many portions of the Earth [*Philander*, 1990].

Although the precise mechanism of El Niño is still not completely understood, the most recent models present several steps in the evolution of a typical El Niño event. During normal years, the trade winds blow strongly from the east to the west across the equatorial Pacific. Water warmed by the sun flows westward in surface currents to pool in the western Pacific and also flows poleward due to Ekman drift. Several months before El Niño warming peaks in the eastern Pacific, the trade winds relax and the westward surface currents slow, as does the Ekman drift. During extreme El Niños, the winds may even reverse, causing the westward currents to disappear and eastward currents to appear along the equator.

These wind changes can force downwelling equatorial Kelvin waves. Kelvin waves have wavelengths of several thousand km and move eastward along the equator at speeds of 2-3 m/sec. Kelvin waves can cause currents which advect some of the water from the warm pool in the west eastward [*Harrison and Schopf*, 1984], but they mainly cause a deepening of the thermocline in the eastern Pacific, which leads to a rise in sea level. The heating of the eastern Pacific intensifies as surface currents continue to bring warm water from the west and

also because the solar insolation has not changed significantly but the advection of warm water out of the eastern Pacific has slowed. Thus, El Niño is essentially an interannual change in where heat is stored in the equatorial Pacific. The increase in heating in the eastern Pacific causes ocean temperatures to increase and, since water expands when it warms, the sea level rises as well.

Remote sensing from satellites has helped to improve our knowledge of El Niño, from sea surface temperature measurements made by meteorological satellites to measurements of sea level elevation made by satellite altimeters. This paper will discuss the role of satellite altimeters in detecting El Niño signatures in sea level elevation as well as the use of altimetry to study the ocean's role in variations in Earth rotation during El Niño events.

## SATELLITE ALTIMETRY AND EL NIÑO

The satellite altimeter measures the distance from the satellite to the ocean surface by transmitting a radar pulse and measuring the time it takes for the reflected pulse to return. The range must be corrected for atmospheric effects which slow down the pulse, and many thousand pulses are averaged together to obtain a single 1-sec measurement [*Stewart*, 1985]. If the altitude of the satellite above a reference ellipsoid is known precisely, then the sea surface height (SSH) can be determined quite accurately by computing the difference

$$\text{SSH} = \text{satellite altitude} - \text{range}. \quad (1)$$

For the TOPEX/POSEIDON (T/P) satellite, the accuracy of the SSH is estimated to be about 5-6 cm for a 1-sec measurement [*Fu et al.*, 1994]. However, much of the error is due to random noise, and if appropriate smoothing is used, the accuracy can increase to about 2-3 cm [*Cheney et al.*, 1994; *Mitchum*, 1994], which is comparable to tide gauge measurements made at the ocean's surface. T/P flies along a repeat track of about 10-days, with coincident ground tracks separated by about 2.8° at the equator. This means that T/P repeats measurements at nearly the same geographical location every 10 days.

The SSH is of the order of several hundred meters, but most of this is due to the Earth's gravity field and steady ocean circulation features, and is unchanging. Since variations in SSH caused by El Niño are several order of magnitudes smaller than the SSH, the mean sea surface at each geographic location is removed and sea level anomalies (SLAs), variations in the sea level from the mean, are computed [*Chambers et al.*, 1998a]. A map of SLAs in the tropical Pacific from T/P for the 10-day cycle from December 9 to 19, 1997 is shown in Figure 1. This time period is during the peak of the 1997 El Niño. Sea level throughout the central and eastern Pacific is 15 to 30 cm higher than normal, while sea level in the eastern Pacific is lower than normal. This is due to the changes in oceanic heat storage in the tropical Pacific during El Niño [*Chambers et al.*, 1998b]. It is important to note that the heating changes do not take place in only the top few meters of the ocean, but in fact take place to a depth of 100-150 m (Figure 2). The subsurface temperature changes are often significantly larger than temperature changes at the surface. It is because such a large layer of water is warmed that the sea level rise is large enough to detect.

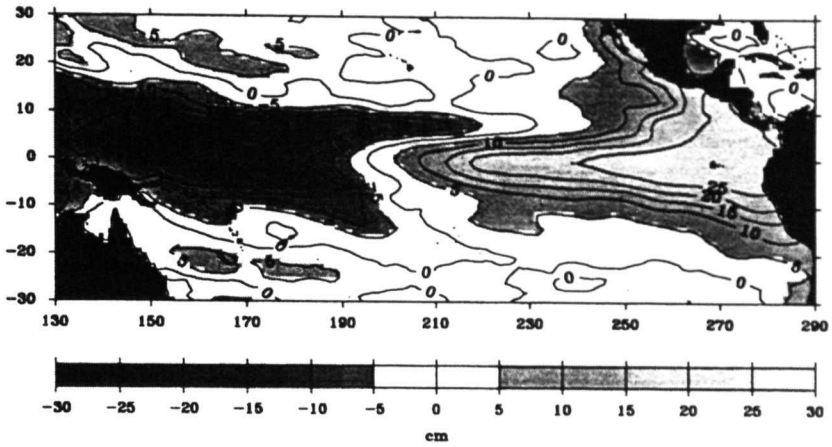


**Figure 1.** Sea level anomalies observed by T/P from December 9-19 1997. The mean annual signal has been removed. Data have been processed and filtered as described in *Chambers et al.* [1997a].

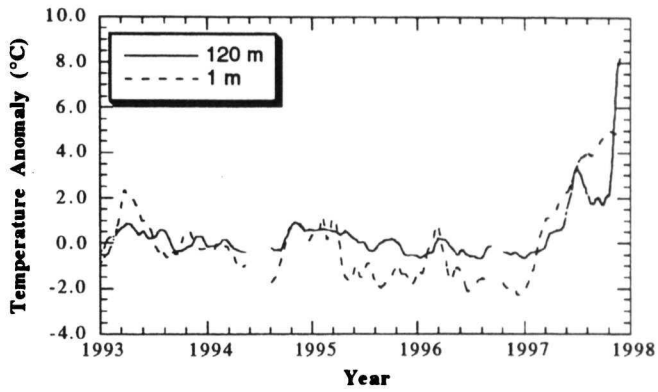


**Figure 3.** Temperature anomalies recorded by a moored buoy at 2°S, 265°E at depths of 1m and 120 m. Data have been smoothed with a running-mean boxcar filter with a window of 30 days.

Not only can altimetry detect and measure El Niño signals after it has formed, altimetry can also detect important precursors to El Niño weeks to months before sea level begins to rise significantly in the eastern Pacific. The role of Kelvin waves at the beginning of an El Niño has already been discussed. For many years, it was theorized that strong Kelvin waves should precede an El Niño because of the wind changes in the western Pacific. However, it was difficult to observe Kelvin waves unequivocally with the scattered in situ measurements available before altimetry [*Knox and Halpern*, 1982; *Eriksen et al.*, 1983]. *Miller et al.* [1988] provided the first complete observations of the sea level variations caused by a large Kelvin wave before El Niño warming developed in the eastern Pacific by using data from the Geosat altimeter satellite. However, the Kelvin wave was discovered significantly after the El Niño had developed during 1987.

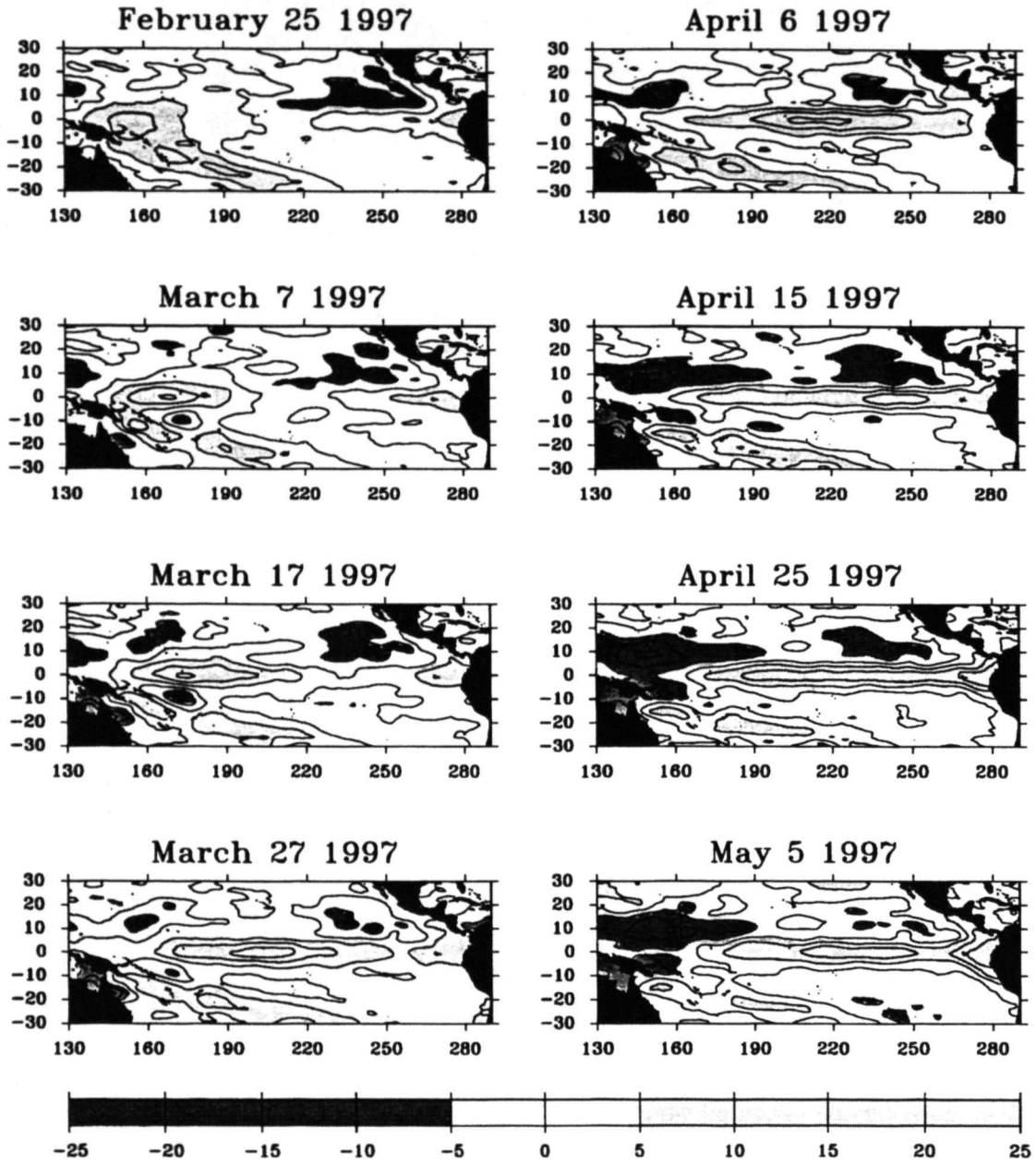


**Figure 4.** Sea level anomalies in cm observed by T/P from February to May 1997 showing progression of a Kelvin wave from the western Pacific to the east along the equator. The date above each picture is the start of a 10-day repeat cycle. Data have been processed and filtered as described in *Chambers et al.* [1997]. SLAs smaller than – 5 cm have been shaded dark gray and SLAs greater than 5 cm have been shaded light gray.

Large Kelvin waves have continued to be observed in satellite altimeter data since the study by *Miller et al.* [1988]. However, most of the results have come months to years after the waves and the onset of El Niño, such as observations by T/P of a Kelvin wave before the small El Niño of 1993 [*Tapley et al.*, 1994]. Recently, though, observations of sea level anomalies from T/P are available over the internet within a few days to a month after the measurement is made, which allows near realtime tracking of Kelvin waves.

An example of T/P observing Kelvin waves during the 1997 El Niño is shown in Figure 4. In late February, sea level was already beginning to rise in the eastern Pacific after an earlier Kelvin wave had reached the coast of South America. Between February 25 and March 7, sea level increased dramatically along the equator in the western Pacific between 150°E and 190°E. Ten days later, the front of this region of large, positive SLAs had moved eastward, indicative of a downwelling Kelvin wave. Over the next month, the Kelvin wave crossed the Pacific and by the beginning of May sea level was more than 15 cm higher than normal off the coast of South America. Sea level was also significantly higher than normal throughout the central and eastern equatorial Pacific, indicating that El Niño warming was beginning.

## EFFECT OF EL NIÑO ON EARTH ROTATION

Studies have shown that time series of the Earth's length of day (LOD) have interannual variations similar to El Niño [e.g., *Rosen et al.*, 1984]. However, the dominant portion of the nontidal signal at most frequencies can be attributed to mass variations within the atmosphere [e.g., *Eubanks et al.*, 1985]. Generally the day is slightly longer than normal during an El Niño. Although the LOD and the effect of the atmosphere on LOD have been studied to some degree, the effect of mass variations in the ocean is more poorly understood.

The sea level measured by altimetry changes because of variations in the density of the ocean. As already noted, water expands (the density decreases) as it warms with no change in mass. However, precipitation, evaporation, and transport of water with differing salinity also effect the density by changing the mass in a particular location. The first effect should cause no fundamental change in the LOD since mass remains constant, but the second effect may contribute to a variation in LOD.

The global mean sea level variation measured by T/P shows a very strong increase in mean sea level correlated with the 1997 El Niño (Figure 5). However, several recent studies have shown that much of the sea level variation is caused by thermal expansion [*White and Tai*, 1995; *Chambers et al.*, 1997, 1998b; *Wang and Koblinsky*, 1997; *Stammer*, 1997].

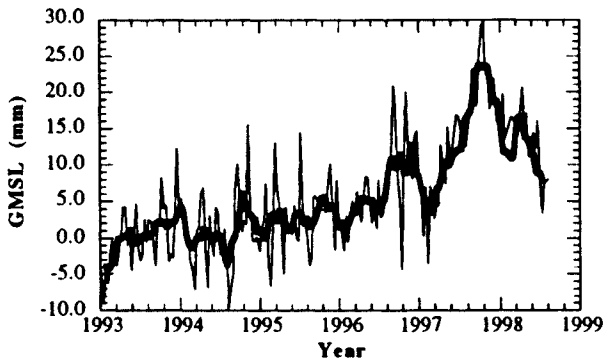


**Figure 5.** Global mean sea level variations from T/P. The thick solid line shows the time series after applying a 60-day running mean boxcar filter. The time series has been computed as suggested by *Nerem* [1995].

This is demonstrated in Figure 6, where sea level variations from T/P are compared to sea level variations computed from thermal data on moored buoys that are part of the NOAA Tropical Atmosphere-Ocean (TAO) program in the Pacific [*McPhaden*, 1993]. Only in the west Pacific is there a significant difference in sea level at interannual frequencies, caused by mass variations due to changes in precipitation/evaporation during El Niño events [*Chambers et al.*, 1998b]. However, even in the western Pacific, the sea level change due to mass variations is much smaller than the sea level change due to thermal expansion.

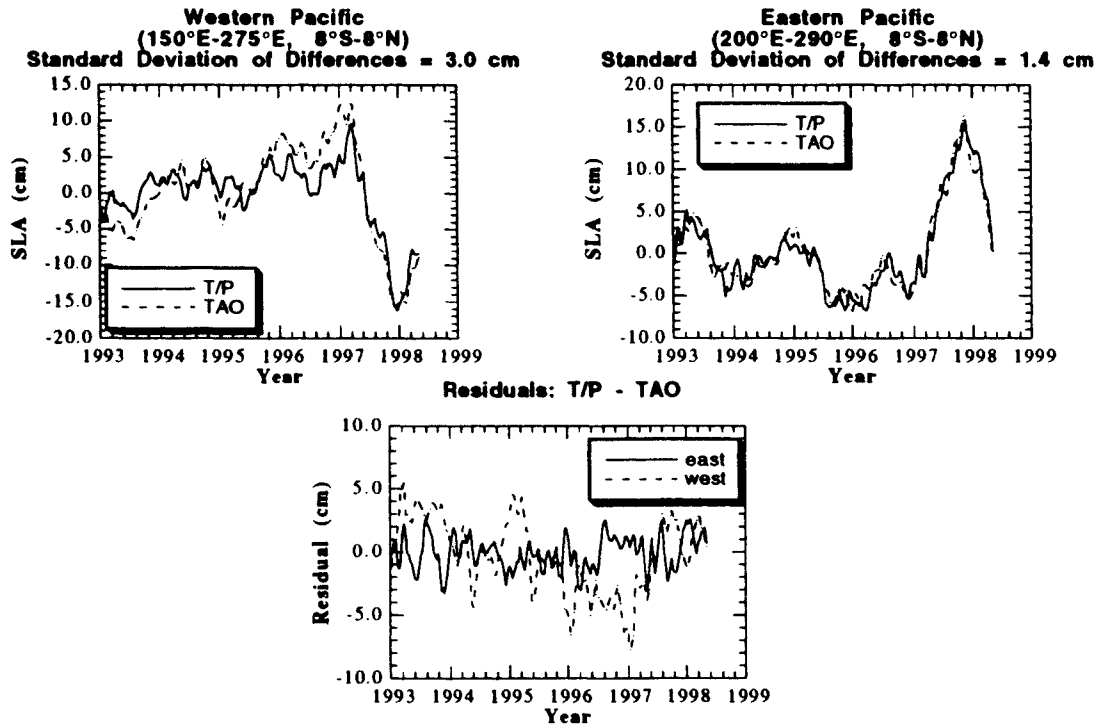


**Figure 6.** Sea level anomalies in western and eastern Pacific from T/P and TAO thermal data (top) and the residual after subtracting thermal sea level variations from T/P (bottom). Data are compared only around TAO buoys and have been smoothed with a running-mean boxcar filter with a window 30 days. The mean annual signal has been removed.

Although altimetry alone cannot separate between thermal and mass effects, by combining altimetry with other measurements of the thermal sea level variation, an approximation of the mass variations can be determined [*Chen et al.*, 1998a,b]. To do this, thermal sea level variations have been computed from an annual climatology [*Levitus and Boyer*, 1994] away from the equatorial Pacific and from TAO buoys near the equatorial Pacific, interpolated to a uniform 1° grid. The thermal sea level variations are then subtracted from gridded T/P SLAs to form a residual of mass variations. The residuals are then integrated globally to compute LOD variations [*Chen et al.*, 1998b]. The results are plotted in Figure 7, along with the LOD computed by the International Earth Rotation Service (IERS) [*IERS*, 1998], and LOD from an atmospheric model [*Salstein and Rosen*, 1997].

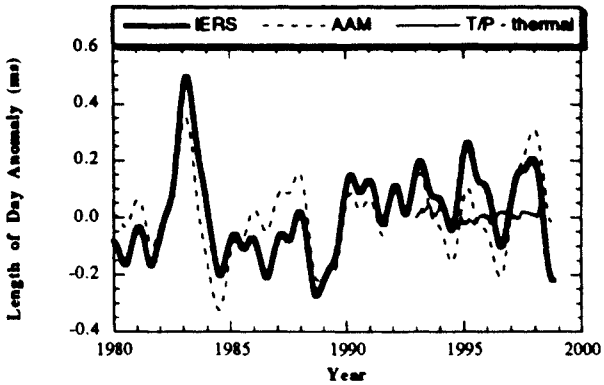


**Figure 7.** Interannual variations in total length of day from observations (IERS), atmospheric angular momentum (AAM) from a model, and the oceanic contribution from T/P minus thermal sea level variations. Tidal signals have been removed. A decadal signal has been removed from the IERS time series.

While the change in LOD near the end of 1997 appears to be smaller than the changes during the 1982 and 1994 El Niño events, much of this is due to uncertainty in the estimation of the decadal trend near the end of the time series. Different estimates can increase or decrease the amplitude during the 1997 event. However, the important message in Figure 7 is the relative contribution to interannual changes in LOD from oceanic mass variations. Based on the T/P altimetry results, after estimating and removing thermal expansion effects, the oceanic contribution to LOD is quite small during an El Niño. This is because El Niño largely causes changes in oceanic heat storage and not mass.

## CONCLUSIONS

TOPEX/POSEIDON has proven very valuable for tracking and monitoring the strength of the 1997 El Niño, since accurate data are available within a month of the initial observation. T/P was able to track Kelvin waves before El Niño signals began to appear in the eastern Pacific, and the altimeter data was useful for monitoring the size and extent of El Niño warming throughout 1997. However, since most of the sea level variations are caused by thermal expansion, the oceanic portion of the LOD signal was very much smaller than the signal from the atmosphere.

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