# ENSO AND ALTIMETRY

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## INTRODUCTION

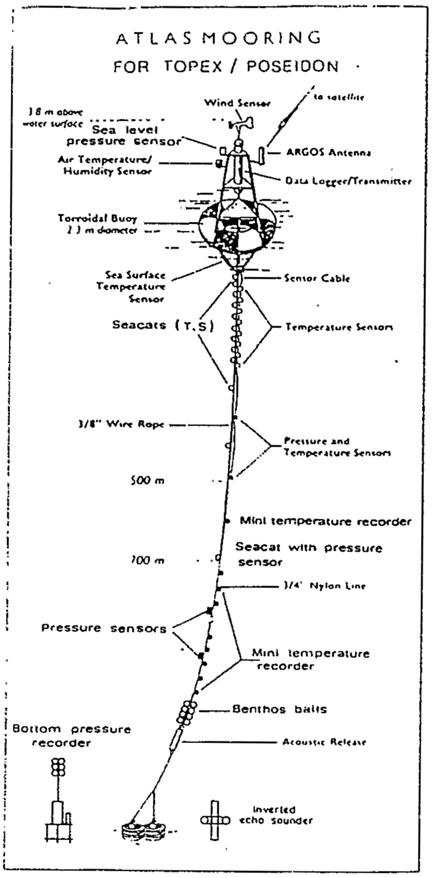
With the growing concern about climate change, and in particular ENSO, satellite altimetry is becoming a very useful tool as it is the only means to observe the variations of sea surface height and the derived surface geostrophic current on a global scale. The U.S. Navy satellite GEOSAT was put into a repetitive orbit just at the beginning of the 1986-87 El Niño, and its mission covered the ensuing 1988-89 La Niña. The U.S./France TOPEX/POSEIDON satellite was designated for the expressed purpose of studying ocean circulation. Its launch in August 1992 occurred when the 1991-94 long-lasting El Niño was underway. Both missions proved to be valuable for the description and understanding of ENSO.

## VALIDATION OF ALTIMETER DATA

The primary goal of satellite altimetry missions is the study of large-scale ocean circulation. With the vanishing Coriolis force toward the equator, very accurate sea level is needed in equatorial regions. Given the numerous corrections involved in measuring sea level from space (e.g., orbit, instrumental, environmental), in situ validation is a fundamental step prior to any use of altimetry data. In any case, it should be kept in mind that an altimeter measures the ocean surface height (i.e., the dynamic topography together with the geoid height), and with the present indetermination of the geoid and its consequent removal, the following studies present sea level and surface current anomalies relative to some mean.

The TOGA sea level, XBT and TAO networks were intensively used for the validation of GEOSAT large-scale sea level measurements (e.g., Cheney et al., 1989; Wyrtki and Mitchum, 1990; Delcroix et al., 1994) with mean correlation and rms difference ranging respectively from 0.6 to 0.8 and 6 cm to 4 cm. The anticipated 2-3 cm accuracy of TOPEX/POSEIDON altimeter data for the detection of large-scale sea level seems to be achieved from further use of these networks (e.g., Cheney et al., 1994; Menkes et al., 1995). Given the intrinsic error of most in situ sea level estimates (3 to 7 cm), a rigorous open-ocean validation experiment was conducted in the western equatorial Pacific Ocean during the Verification Phase of the TOPEX/POSEIDON mission. Two TOGA-TAO moorings were outfitted with additional temperature, salinity, and pressure sensors to measure within 1 cm the dynamic height from the surface to the bottom at 5 mn intervals directly beneath two TOPEX/POSEIDON crossovers (Picaut, et al., 1995). Instantaneous comparisons with the 1 sec TOPEX/POSEIDON altimeter retrievals and the 5 mn dynamic height resulted in a rms difference as low as 3.3 cm at 2°S-164°E and 3.7 cm at 2°S-156°E. After the use of a 30-day low-pass filter, in situ and satellite data were found to be highly correlated (Figure 1).

The applicability of satellite altimeter data for estimating zonal surface current variability at the equator was assessed using the meridionally differenced form of the geostrophic balance. Altimetry-derived geostrophic estimates agree well with near-surface zonal current observed from TOGA-TAO moorings along the equator (Picaut et al., 1990). Given the sensitivity of the geostrophic approximation to small sea level variations near the equator, this represents the most stringent test of the use of altimetry observations to estimate sea level and surface currents.



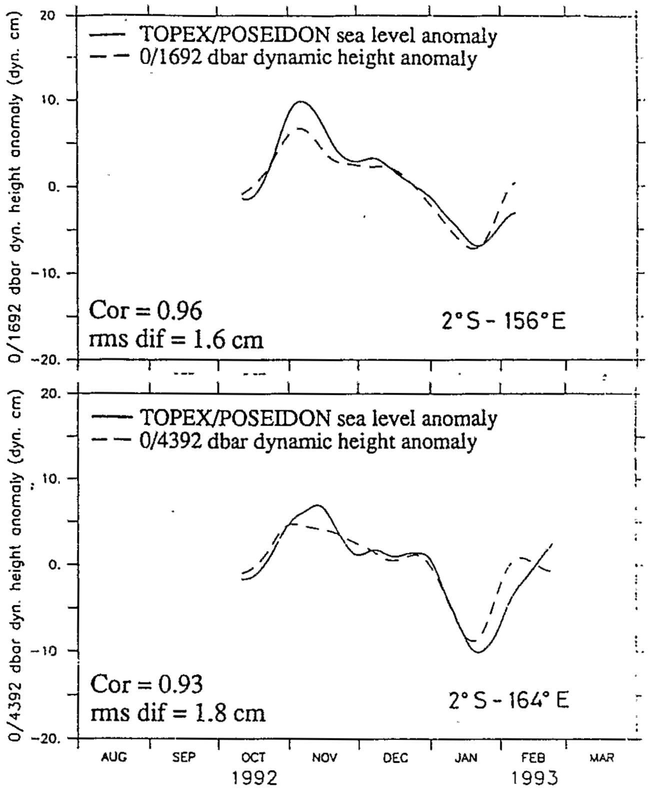




**Figure 1** - Left panel: TAO mooring design with additional instruments along the line. Right panel: low frequency comparison between the sea surface dynamic height relative to the bottom and the TOPEX/POSEIDON sea level (from Picaut et al., 1995).

## ENSO WAVE ACTIVITY EVIDENCED FROM ALTIMETRY

Cheney et al. (1987) and Miller et al. (1988) were the first to clearly evidence several equatorial downwelling Kelvin waves during the onset of the 1986-87 El Niño with GEOSAT derived sea level. These waves, excited by westerly wind bursts in the western equatorial Pacific, propagated across the Pacific Ocean with phase speeds of about 2.5 m $s^{-1}$. Delcroix et al. (1991), through basin-wide analysis of GEOSAT sea level and derived surface currents, evidenced equatorial Rossby waves during the 1986-87 El Niño. In particular, an upwelling Rossby wave crossed the equatorial basin from March to September 1987. Two independent estimates of equatorial trapping scale (fitted to the theoretical meridional sea level structure) and of phase propagation clearly indicate this wave to be a first baroclinic first meridional mode (Figure 2).

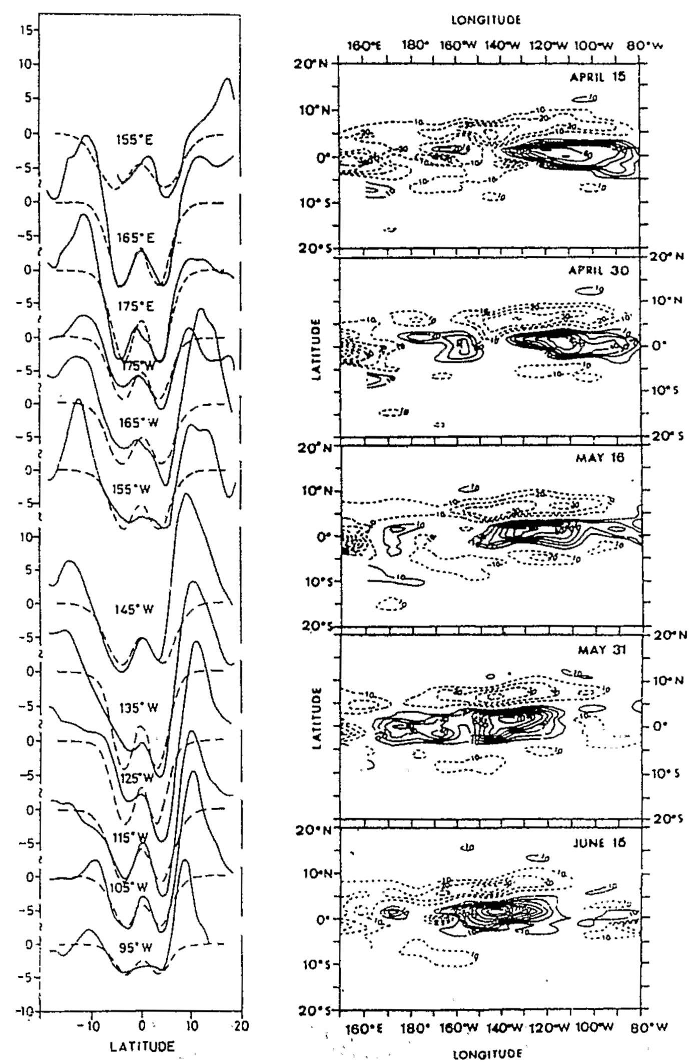



**Figure 2** - Left panel: least squares fits of the upwelling GEOSAT sea level anomalies (in cm, solid curve) to the theoretical meridional structures (dashed curves) of a first meridional equatorial upwelling wave. Right panel: time/space representation of the GEOSAT zonal surface geostrophic current anomalies from April 15 to June 15, 1987. Contour interval is 10 cm $s^{-1}$. Its depicts the westward propagation of the upwelling equatorial Rossby waves from the eastern to the central Pacific (from Delcroix et al., 1991).

The surface currents, associated with the passage of this upwelling Rossby wave during the peak phase o the 1986-87 El Niño, strongly affected the South Equatorial Current and the North and South Equatoria Coutercurrents. The following La Niña event in 1988-89 is also associated with upwelling Kelvin wave evidenced from GEOSAT altimetry (Delcroix et al., 1994).

The launch of TOPEX/POSEIDON in August 1992 occurred during the second phase of the extended 1991-94 El Niño. Analysis of the space-time structure in the TOPEX sea level together with TOGA-TAO surface dynamic height anomalies indicates sea level variability primarily due to equatorial Kelvin wave activity generated by westerly wind burst west of the date line (Busalacchi, et al., 1994). This El Niño persisted up to the 1994-95 boreal winter, with equatorial wave activity clearly evidenced by TOPEX/POSEIDON.

## TEST OF ENSO THEORY, SEARCH FOR MECHANISMS

The hypothesis of Wyrtki (1985) of a buildup of water mass in the tropical Pacific prior to an El Niño was tested in a study by Miller et al. (1990) using GEOSAT data. It was suggested that Wyrtki's upper volume estimate is only representative of the equatorial band rather than of the tropical Pacific as a whole. A sampling study done by Springer et al. (1990) confirmed that the difference is due to inadequate island tide gage coverage, especially in the eastern Pacific. The hypothesis of buildup is unclear, as these two studies did not show a buildup prior to the 1982-83 and the 1986-87 El Niño events.

The delayed action oscillator theory of ENSO involves the reflection of upwelling Rossby waves at the western Pacific boundary into equatorial upwelling Kelvin waves for the termination of an El Niño and its shift into La Niña (Schopf and Suarez, 1988; Battisti, 1988). Through extended EOF analysis of GEOSAT data during the 1986-89 El Niño-La Niña cycle, White and Tai (1992) suggest that equatorial Rossby wave reflected into equatorial Kelvin wave at the western boundary. A detailed study of individual equatorial waves, issued from the projection of GEOSAT sea level and derived surface currents (Delcroix et al., 1994), indicates very little evidence of first meridional Rossby wave reflection into Kelvin waves during the 1986-89 El Niño-La Niña (Figure 3).

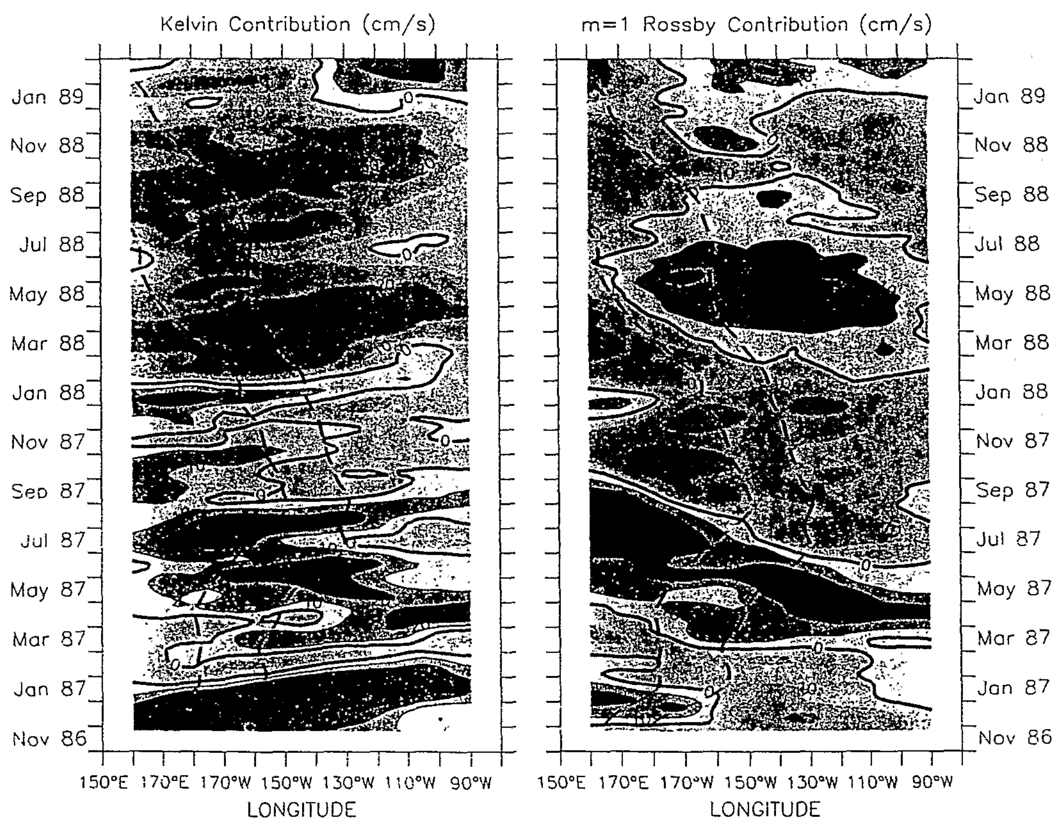



**Figure 3** - Longitude-time distribution of 4°N-4°S averaged surface current anomalies derived from GEOSAT data projected onto first baroclinic Kelvin and first meridional mode Rossby waves. Contour interval is 10 cm $s^{-1}$. Superimposed as heavy dashed lines are the trajectories of two hypothetical drifters moved by these currents (from Picaut and Delcroix, 1995).

The good correspondence, in the western equatorial Pacific, between Kelvin wave forcing and GEOSAT derived Kelvin wave contribution to zonal current (Figure 4), suggests that wind forcing rather than reflected Rossby waves was the main trigger of Kelvin waves. Similar results were also found during the second phase of the 1991-94 El Niño through TOPEX/POSEIDON data analysis (Boulanger and Menkes, 1995). Both studies do not plead in favor of the ENSO delayed action oscillator mechanism.

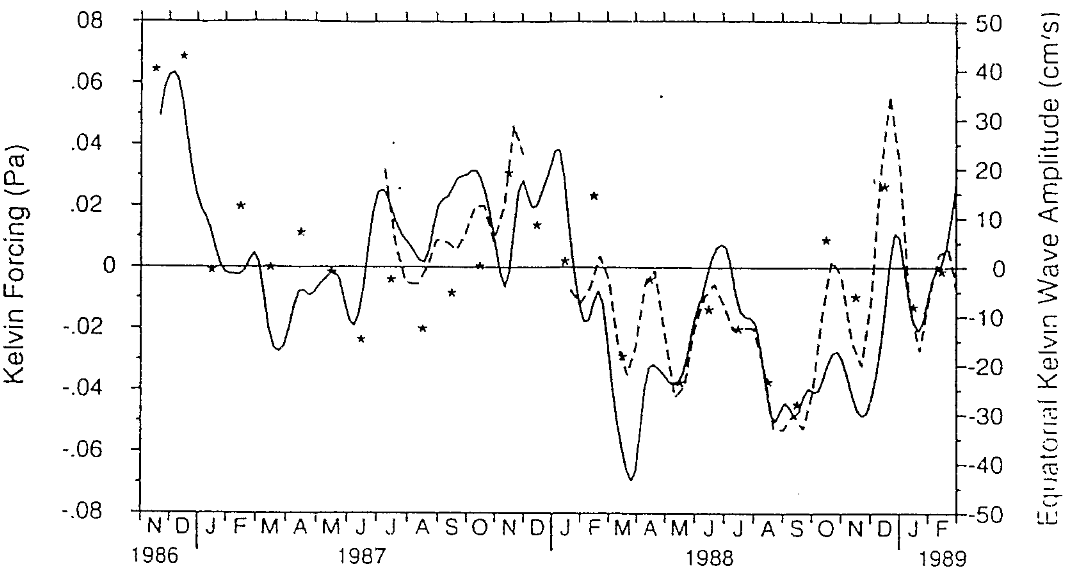



**Figure 4** - Time series of 130°E-160°E averaged Kelvin forcing anomaly derived from the special sensor microwave imager (dashed line) and Florida State University wind product (stars) and equatorial Kelvin amplitude at 0°-160°E (solid line), (from Delcroix et al., 1994).

Another concept is proposed for the shift of El Niño into La Niña, at least during the successive 1986-89 El Niño-La Niña (Picaut and Delcroix, 1995; Picaut et al., 1995, this volume). Using hypothetical drifters moved with the <4°N-4°S> GEOSAT-derived surface currents (Figure 3), these authors found out that the zonal displacement of the eastern edge of the warm pool during the successive 1986-89 El Niño-La Niña was mainly caused by horizontal advection by zonal current anomaly. This suggests that El Niño (La Niña) warm (cold) SST anomaly in the central-western Pacific was the result of anomalous zonal advection. Since the cold SST anomaly in the central-western Pacific, induced by the westward displacement of the eastern edge of the warm pool, was the very first manifestation of La Niña over the whole equatorial Pacific, the turn from El Niño to La Niña in 1987 can therefore be attributed to the change from eastward to westward in the displacement, and therefore from a first meridional mode equatorial Rossby wave, issued from the eastern Pacific (Figure 3).

## MODEL IMPROVEMENT

Due to its global coverage, satellite altimetry appears to be a useful tool for the improvement of tropical ocean models (Cf. Arnault and Perigaud, 1992, for a review). As an example, du Penhoat et al. (1992) have addressed some questions issued from the GEOSAT data analysis of Delcroix et al. (1991) regarding the eastern Pacific boundary reflection during the 1986-87 El Niño. The deficiency of the coupled model of Zebiak and Cane (1987) in simulating and predicting La Niña in 1988-89 seems to be partly explained by the poor ability of the ocean model in advecting cold water. With the introduction of GEOSAT-derived surface currents in the model and a new parametrization of entrainment, Dewitte and Perigaud (1995) were able to reproduce La Niña in 1988-89. The Zebiak and Cane model was also unable to predict the second El Niño event of 1993. However, the model initialized with TOPEX sea level anomalies added to the mean sea surface dynamic height deduced from historical XBT data, leads to the prediction of this specific event seven months ahead (Claire Perigaud, personal communication, 1995). Yet, much more studies are needed to undeniably prove that altimetry is useful for short-term climate prediction.

## CONCLUSION

Validation studies in the equatorial Pacific indicate that satellite altimetry is now accurate enough to detect sea level variations within a few centimeters and geostrophic surface current anomalies within tens of centimeters per second in the equatorial band. Altimetry appears therefore as a powerful tool for studying basin-wide ENSO sea-level and derived surface current anomalies in the tropics. During the 1986-89 El Niño-La Niña, equatorial wave activity was notable and zonal advection appeared to be the main mechanism for SST changes in the central-western equatorial Pacific. Specific studies, on the 1986-89 ENSO cycle and on the 1992-93 warm event, indicate that wind forcing rather than wave reflection at the western boundary was the main forcing of equatorial Kelvin waves, in contrast to recent ENSO theory. All these studies and others strongly advocate altimetry for the observation, understanding and simulation of ENSO.

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