GEOSAT Sea Level Anomalies in the Western Equatorial Pacific during the 1986-87 El Nino, Elucidated as Equatorial Kelvin and Rossby Waves

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ABSTRACT

Thanks to the GEOSAT altimeter data set, information on sea level changes during the 1986-87 El Nino is presented. Special emphasis is placed on the warm pool area, with an evaluation, a detailed description and tentative explanation of the observed Sea Level Anomaly (SLA) changes.

Near the 165°E longitude, the onset of the 1986-87 El Nino is characterized by a rapid development of a positive (>14 cm) equatorial SLA in November/December 1986. This feature occurs in response to an eastward wind anomaly appearing between 140°E-170°W along the equator. The wind induces a downwelling equatorial Kelvin wave with phase speed of about 2.3 $m.s^{-1}$. Thereafter, equatorial SLA remains quite constant from January to April/May 1987. In June 1987, equatorial SLA decreases to a minimum value, just after an abrupt change of the zonal wind stress anomaly, west of 165°E. Such anomaly seems to force an upwelling equatorial Kelvin wave propagating at about 2.3 $m.s^{-1}$. Two patches of negative SLAs then appear in September 1987 at 4°N and 4°S, symmetrical about the equator. These are the signature of a first baroclinic upwelling equatorial Rossby wave (n=l=1) arising from the eastern boundary, at c = 0.9 $m.s^{-1}$ phase speed. These calculations suggest that first baroclinic mode Kelvin waves and Rossby wave were the dominant sources of sea level changes in the equatorial band, over the November 1986-November 1987 El Nino period.

1. Introduction.

Before 1985, large scale monitoring of the tropical Pacific Ocean relied on island sea level and/or XBT networks. Both monitoring approaches were quite successful in describing and understanding the main tropical Pacific Ocean variability (e.g., Wyrtki, 1985; White et al., 1985). However, these observations were respectively limited by the poor spatial coverage of the islands, especially in the eastern Pacific, and the poor temporal resolution of XBT measurements which were also restricted to commercial shipping routes.

The U.S. Navy GEOSAT (GEOdetic SATellite) was launched in March 1985, which coincided with the beginning of the international TOGA programme. Hence, the 1986-87 El Nino phenomenon was the first to be captured by a satellite altimeter, providing unprecedented spatial and temporal resolutions of the tropical Pacific ocean surface variability.

Previous works (Cheney and Miller, 1988; Miller et al., 1988; Tai et al., 1989) have already demonstrated the usefulness of GEOSAT in monitoring the whole tropical Pacific ocean. As a complement, the goal of this note is to specifically focus upon the Sea Level Anomalies (SLAs) measured in the tropical Pacific warm pool during the 1986-87 El Nino. To this end, we first briefly present the GEOSAT data and data processing, then give a description of the SLAs observed in the "center" of the warm pool (165°E longitude), and finally try to understand the origin of the altimeter-derived SLAs.

2. Data

a. Data processing.

Detailed information about the GEOSAT mission may be found in a review released by the Applied Physics Laboratory of the Johns Hopkins University (APL, 1987). It is worth reiterating here that the GEOSAT spacecraft was originally launched into a non repeat orbit (March 12, 1985), and then put into a 17-day repeat/collinear orbit configuration (November 18, 1987), for oceanographic applications. Only part of that phase of the mission, referred to as the Exact Repeat Mission (ERM), will be considered here.

The GEOSAT data we have analysed were kindly provided by C. Koblinsky (NASA, Greenbelt). All environmental corrections, e.g. water vapour derived from the Fleet Numerical Oceanographic Center's 12-hour model, were already included. The Sea Level Anomalies (SLAs) data we received, stem from the first year of the ERM; SLAs are thus relative to the mean of the November 1986-November 1987 period. The data consist of 22 grids of SLAs, and figure 1 shows the ground tracks of such a grid over the tropical Pacific ocean. Tracks are separated from each other by about 1.5° at the equator, and there is a measurement every about 7 km along each track.

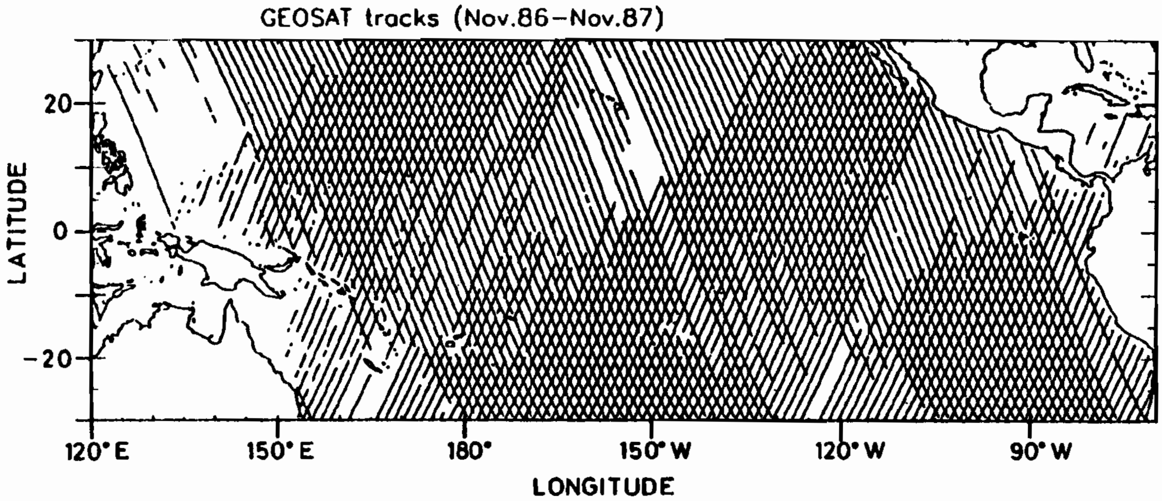


FIG.1. Ground tracks of the GEOSAT 17-day collinear orbit over the tropical Pacific ocean.

Our own data processing was made in three steps. Firstly, along track SLAs were smoothed using 300 km width non-linear median and linear Hanning filters. An example of such processing is given in figure 2. Secondly, by combining several tracks (6-7) in the zonal direction, time series of SLAs were generated in 0.5°x10° latitude-longitude boxes. Finally, smoothed records were produced by low-pass filtering in time and latitude using a 31-day and 3°-latitude Hanning filters. No smoothing in longitude was performed.

b. Evaluation

Comparisons between GEOSAT sea level and data from tide gauges, inverted echo sounders, and thermistor chains at various locations throughout the Pacific have suggested that altimeter time series have an RMS accuracy of about 3 cm (Cheney et al., 1988). As an example of our intercomparison figure 3 shows a GEOSAT SLA time series obtained in the warm pool (2°S-165°E), together with the 0/300db dynamic height anomaly derived from the ATLAS thermistor chain mooring at 2°S-165°E, and the 0/500db dynamic height anomaly obtained from CTD stations made during seven cruises. Although the data may differ by as much as 5 to 12 cm, they generally agree within a few centimeters. Notable

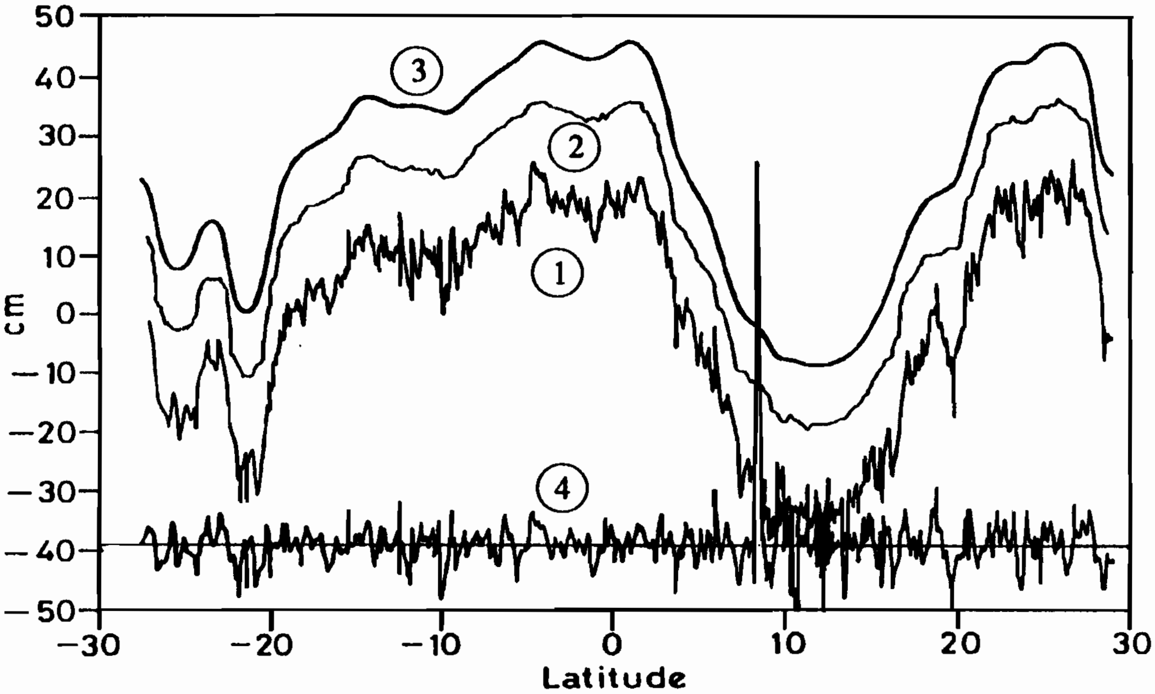


FIG.2. Along track processing of meridional sea level anomalies. Curve 1 denotes the raw sea level anomaly (cm) from 30°S to 30°N. Curve 2 is curve 1 shifted by +10 cm and despiked with a 3°-latitude non-linear median filter. Curve 3 is curve 2 shifted by +10 cm and smoothed with a 3°-latitude Hanning filter. Curve 4 is curve 1 minus curve 3.

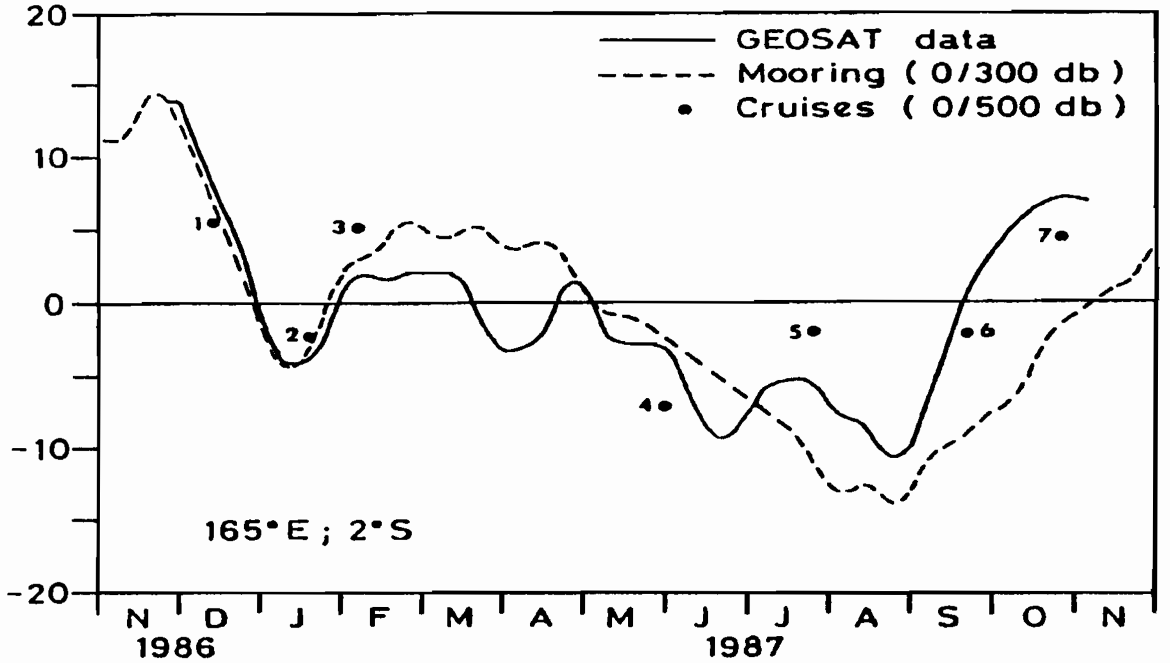


FIG.3. Comparison between Geosat SLA time series (full line), 0/300db dynamic height anomaly time series obtained from ATLAS thermistor chain moorings (broken line), and spot 0/500db dynamic height anomaly measurements derived from CTD stations from seven different cruises. Note that the 0/300 db data were linearly interpolated from May 20 to July 21, 1987. Cruise numbers are (1) US/PRC-2, (2) SURTROPAC-7, (3) JENEX-1, (4) SAGA-2, (5) SURTROPAC-8, (6) PROPPAC-1, and (7) US/PRC-3. The vertical scale denotes either cm (GEOSAT data) or dyn.cm (mooring and cruises).

differences between time series may be due to incomplete correction of environmental errors and/or they may reflect the idiosyncrasies of each type of observations (e.g., the dynamic height time series do not include the variability below 300 db as well as the salinity effects upon dynamic height computation; the CTD stations represent only spot measurements, etc...). The RMS scatter about the fitted line between the altimeter SLAs and the 0/300 db dynamic height anomaly is 4 cm. Thus, based on previous evaluations and on this last comparison, we conclude that GEOSAT altimeter data seems adequate for monitoring sea level variations in the tropics with an RMS accuracy of 4 cm. As a consequence, only SLAs above ± 8 cm, corresponding to a signal/noise = 2, will be further considered.

3. Results

Figure 4 represents the SLAs along the 165°E longitude, as a function of time and latitude. Four patches of SLA above ± 8 cm appear in the equatorial band. Our purpose is to sequentially analyse the mechanisms that generated these patches. In support of this analysis, we will refer to figures 5a-b presenting the zonal wind stress anomaly and SLA along the equator, both as a function of time, from the western to the eastern Pacific.

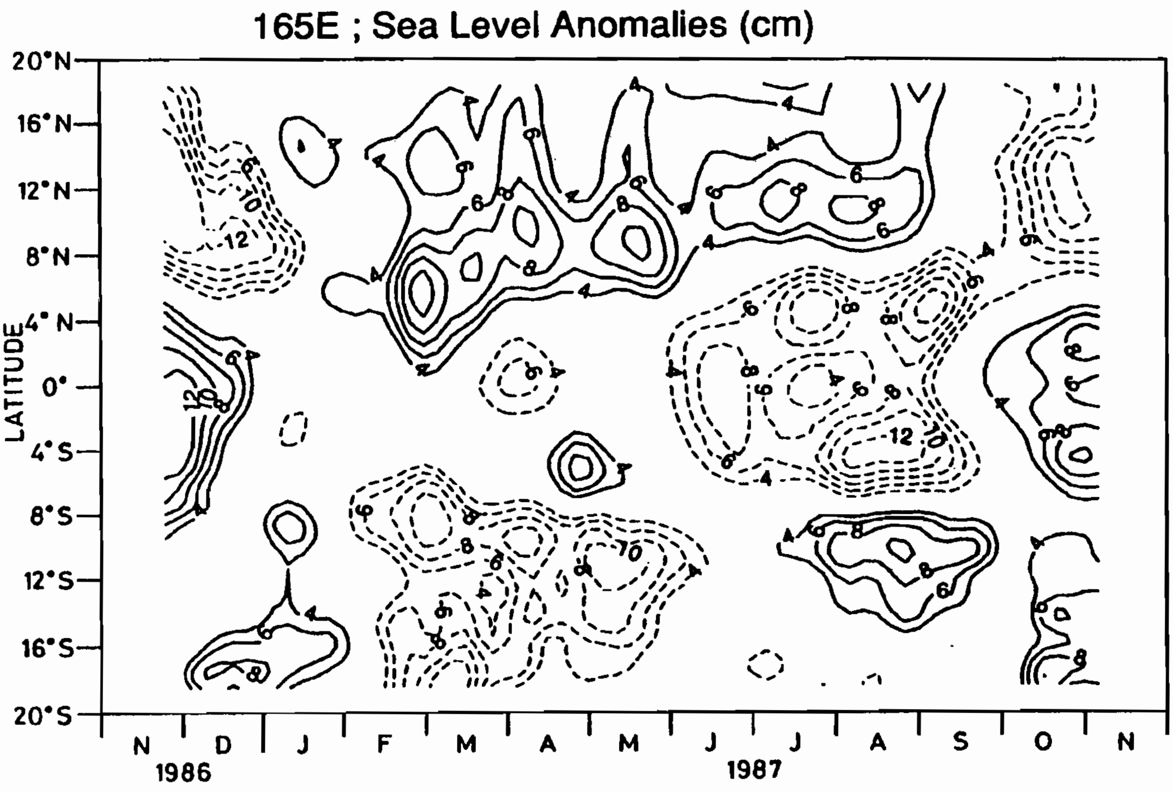
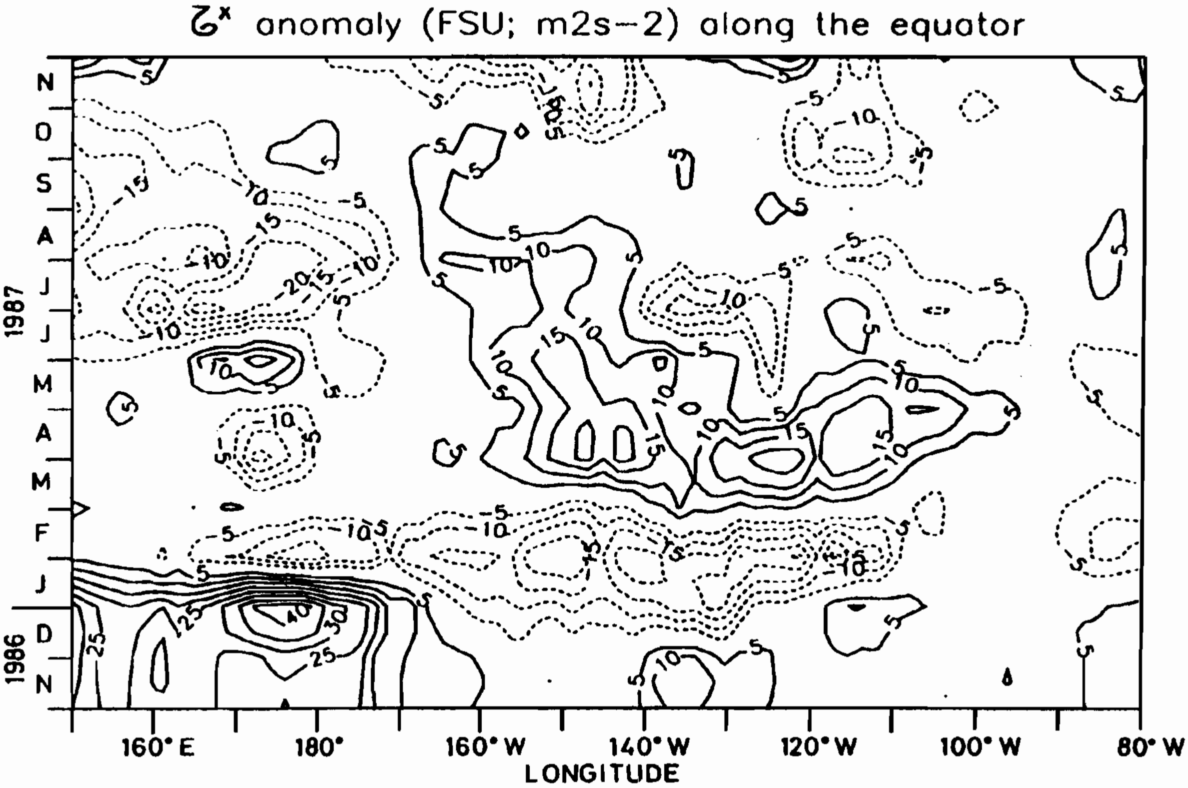


FIG.4. Geosat sea level anomalies (cm) as a function of time and latitude, along the 165°E longitude.

The first significant patch of SLA appears in November/December 986 (Fig.5b). It occurs in response to eastward wind anomaly located west of about 170°W (Fig.5a). The wind induces a downwelling equatorial Kelvin wave which propagates across the entire basin at about the first baroclinic phase speed $c^k{}_1$= 2.3 m.s^{-1} (Eriksen, 1982), as already documented by Miller et al. (1988). A Gaussian fit of the meridional SLA structure, east of the forcing area, is clearly in excellent agreement with the data, within ± 5° of the equator using $c^k{}_1$ = 2.3 m.s^{-1} (Fig.6).



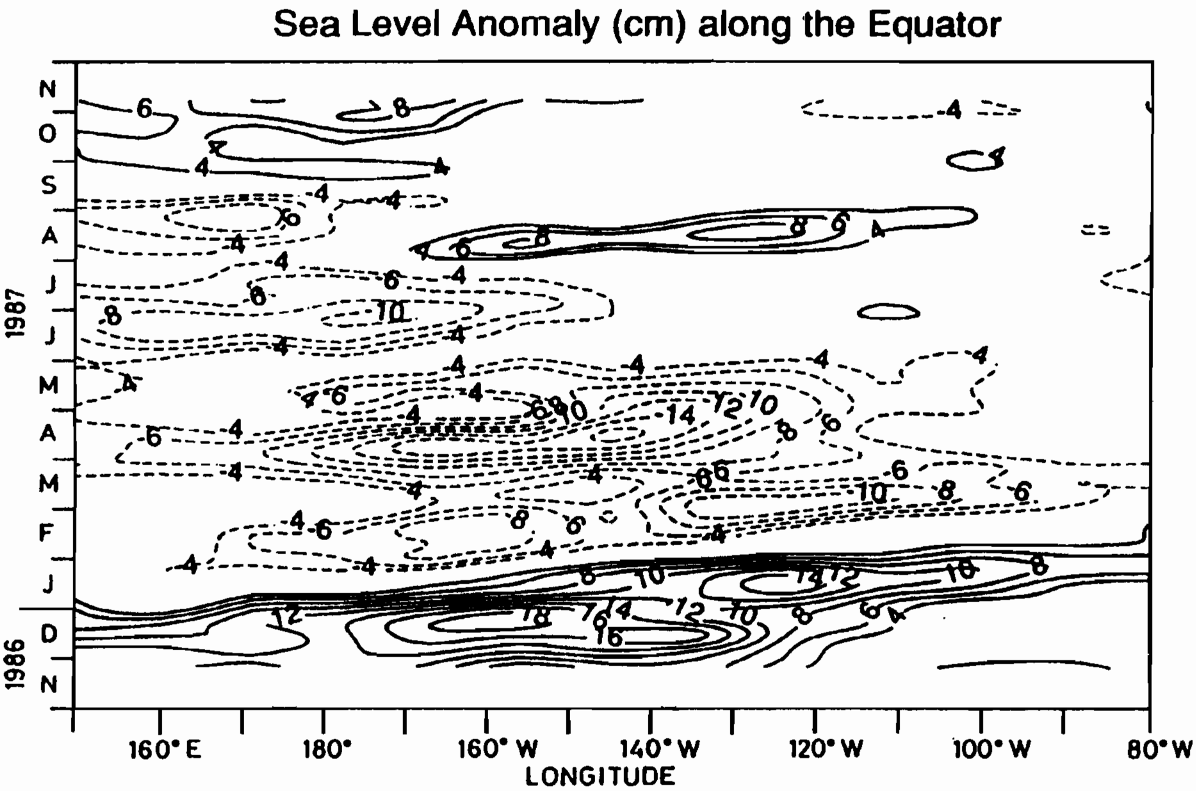


FIG.5. Top (a): Zonal wind stress anomaly ($m^2.s^{-2}$) along the equator as a function of time and longitude;
Bottom (b): Sea level anomaly (cm) along the equator as a function of time and longitude.

The second significant sea level signal emerges in June 1987 (Fig.5b), just after a rapid zonal wind stress change near the 165°E longitude (Fig.5a). The wind seems to generate an upwelling Kelvin wave (Fig.5b) that propagates at least to the middle of the basin, where the Kelvin wave meets a downwelling-favorable wind stress. Figure 7 shows that a Gaussian fit of the meridional SLA structure, east of the forcing area, corresponds quite well to the data, within ± 5° of the equator, using $c^k{}_l$=2.3 m.s^{-1}.

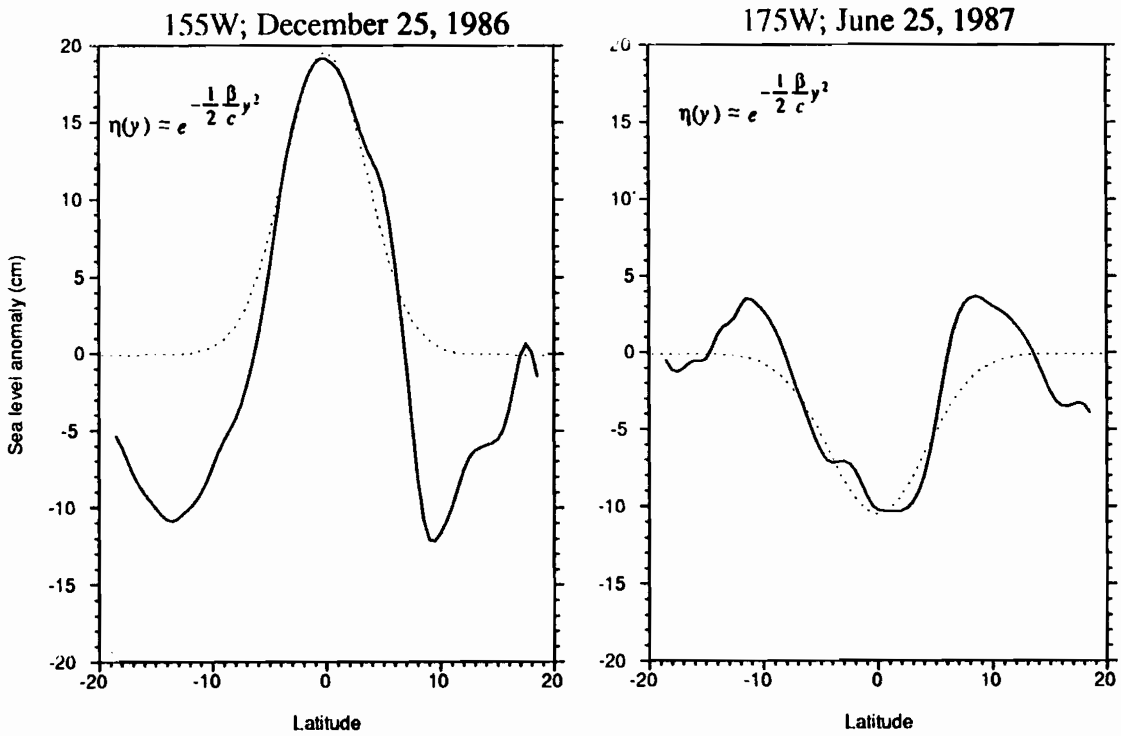


FIG.6. Gaussian fit (broken line) of the meridional (20°S-20°N) sea level anomaly structure (full line) at 155°W longitude, on December 25, 1986.

FIG.7. Gaussian fit (broken line) of the meridional (20°S-20°N) sea level anomaly structure (full line) at 175°W longitude, on June 25, 1987.

Two patches of SLAs in excess of ± 8 cm then arise in August-September 1987, at 165°E, symmetrical about the equator at about 4°N and 4°S (Fig.4). They result from the westward propagation of a first baroclinic (n=1) first horizontal (l=1) Rossby wave, as shown in Figure 8. The Rossby wave propagates at about $c^R{}_1$=0.9 m.s^{-1}, i.e. about one third (2l+1=3) of the aforementionned Kelvin wave phase speed. Figure 10 shows the good agreement between the meridional SLA structure and the theoretical shape of the Rossby wave (n=l=1), involving Gaussian and Hermite functions.

The upwelling Rossby wave portrayed in Figure 8 may result from two different mechanisms. First, due to the excellent timing agreement, we suggest that it might be the reflection of the upwelling equatorial Kelvin wave generated by the fast zonal wind stress change occuring east of 165°E , by the end of January 1987 (Fig.5a). This upwelling equatorial Kelvin wave, evidenced in figure 5b, hits the eastern coast by the end of March 1987, and then might reflect as an equatorial upwelling Rossby wave (Fig.8). Second, it should be noted that the upwelling Rossby wave may also be amplified or eventually generated by local forcing, as exemplified in figure 9 which shows a positive Ekman pumping anomaly beginning in early March 1987, between about 100°W and 160°W.

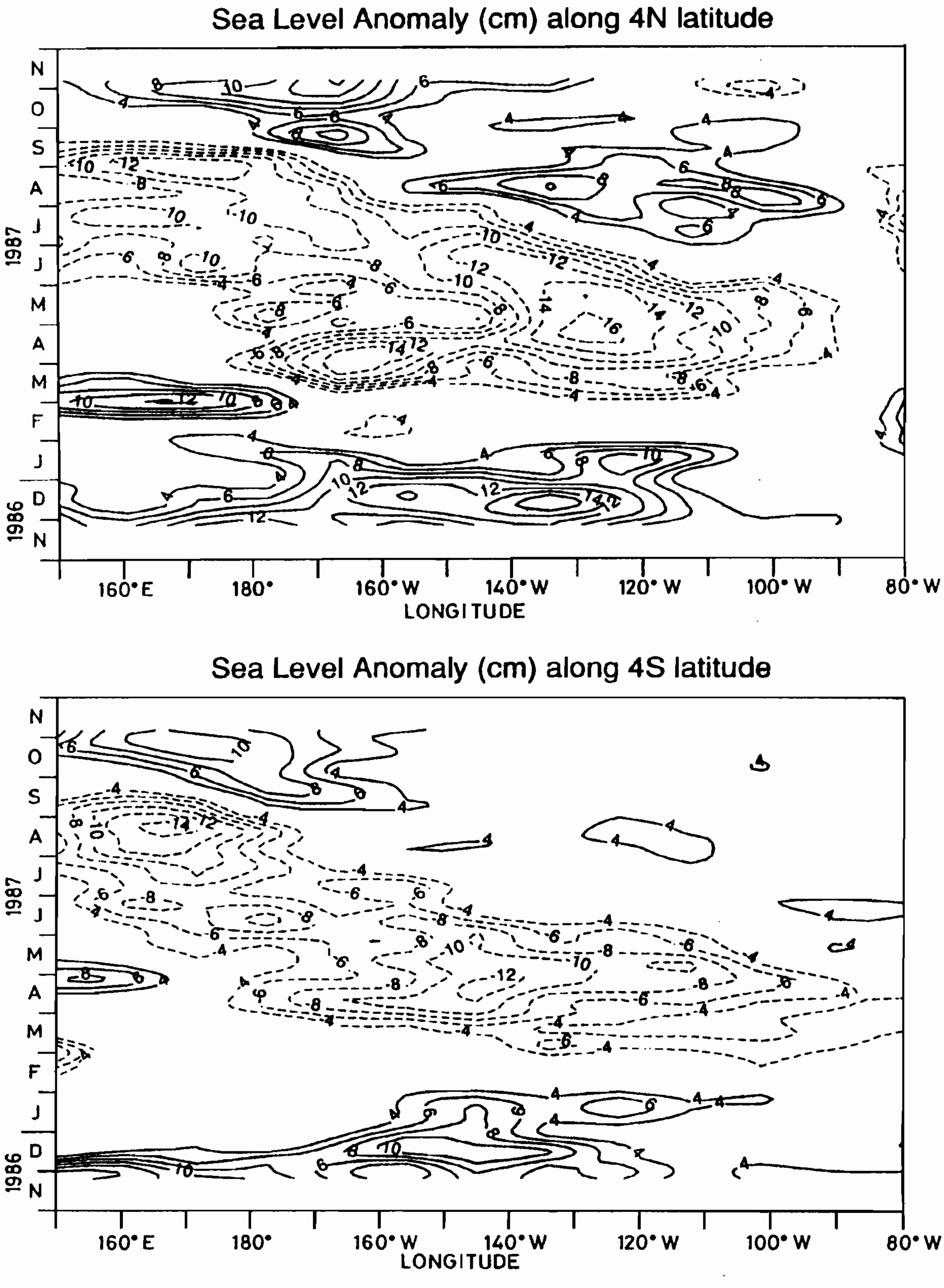


FIG.8. Sea level anomaly (cm) along the 4°N (top panel) and 4°S (bottom panel) latitudes, as a function of time and longitude.

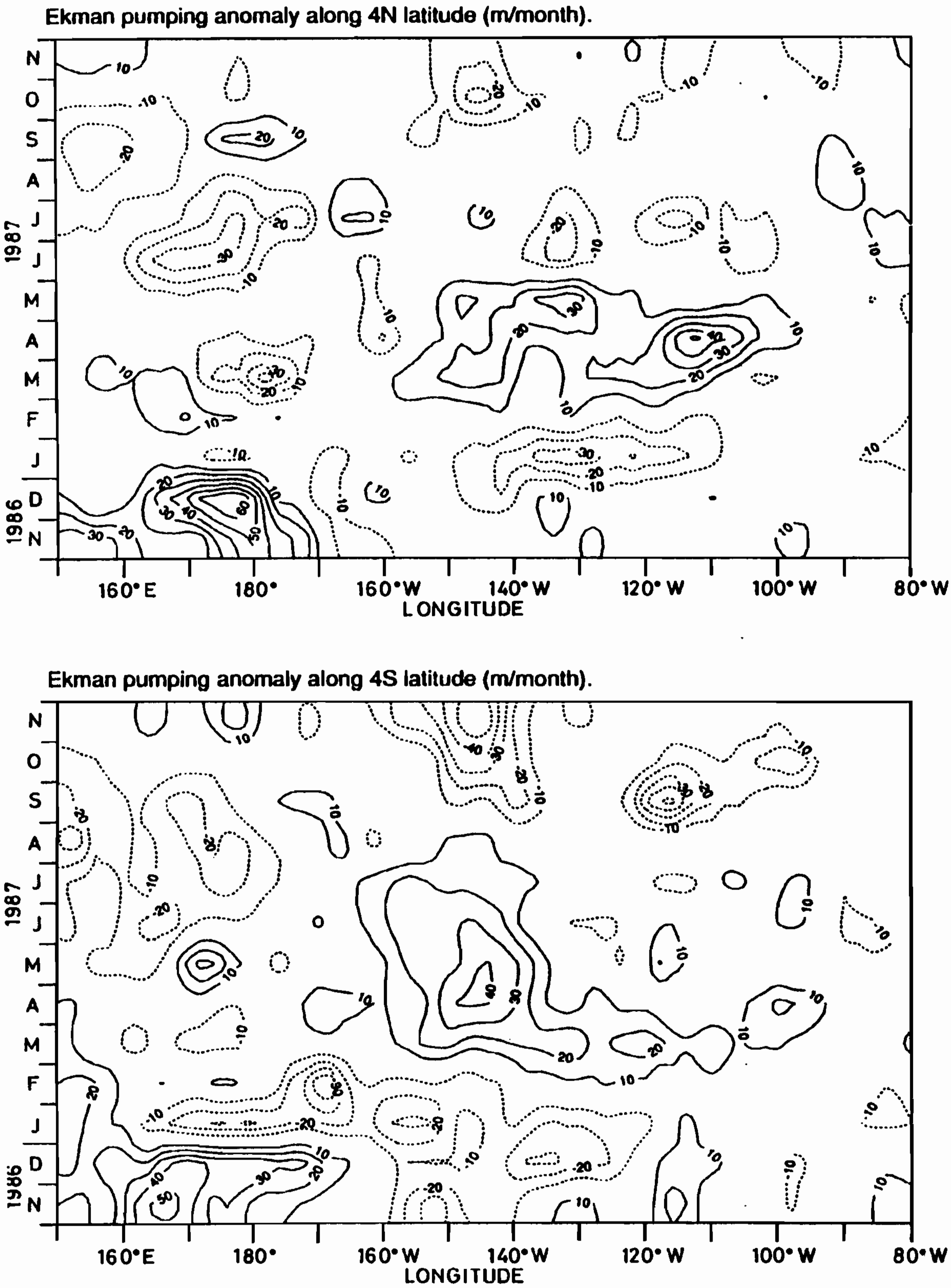


FIG.9. Ekman pumping anomaly (m.month^{-1}) along the 4°N (top panel) and 4°S (bottom panel) latitudes, as a function of time and longitude. Positive value is upward motion.

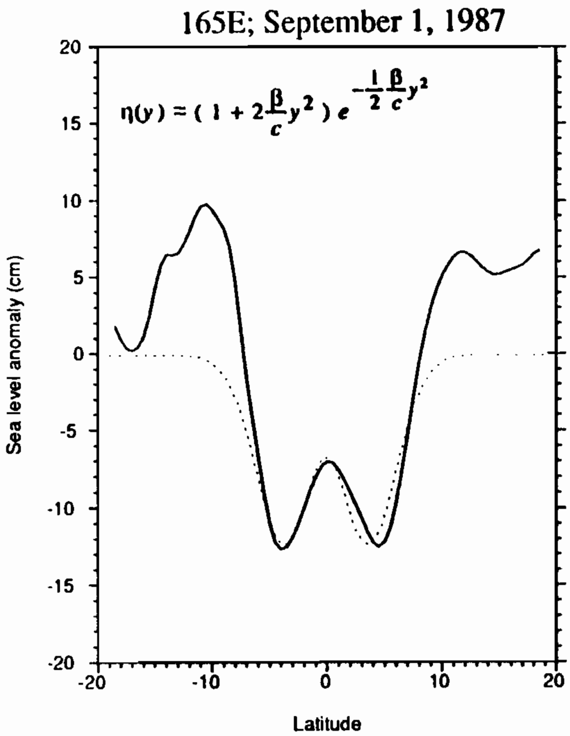


FIG.10. Least square fit (broken line) of the meridional (20°S-20°N) sea level anomaly structure (full line) at 165°E longitude, on September 1, 1987.

The relative importance of both mechanisms is now part of an ongoing study involving linear numerical model results.

In conclusion, we believe that first baroclinic Kelvin waves and (n=l=1) Rossby wave are the dominant sources of sea level changes in the equatorial band, during the 1986-87 El Nino.

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REFERENCES

APL, 1987: The Navy GEOSAT mission, Johns Hopkins Applied Physics Laboratory, technical digest, vol. 8, No 2, 290 pages. (Johns Hopkins Road, Laurel, MD 20707, USA).

Cheney R. and L. Miller, 1988: Mapping the 1986-1987 El Nino with GEOSAT data. *EOS,* 69, 754-755.

Cheney R., B. Douglas and L. Miller, 1988: Evaluation of GEOSAT altimeter data with application to tropical Pacific sea level variability. *J. Geophys. Res.*, **95**, 4737-4749.

Eriksen C., 1982: Equatorial wave vertical modes observed in a western Pacific island array. *J. Phys. Oceanogr.*, **12**, 1206-1227.

Miller L., R. Cheney and B. Douglas, 1988: GEOSAT altimeter observations of Kelvin waves and the 1986-87 El Nino. *Science,* **239,** 52-54.

Tai C.K, W. White and S. Pazan, 1989: Geosat crossover analysis in the tropical Pacific. 2. Verification of altimetric sea level maps with XBT and island sea level data. *J. Geophys. Res.*, **94**, 897-908.

White W., G. Meyers, J.R. Donguy and S. Pazan, 1985: Short term variability in the thermal structure of the Pacific ocean during 1979-82. *J. Phys. Oceanogr.*, **15**, 917-935.

Wyrtki, 1985: Water displacements in the Pacific and the genesis of El Nino cycles. *J. Geophys. Res.*, **90**, 7129-7132.

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