Surface Equatorial Flow Anomalies in the Pacific Ocean During the 1986-87 ENSO Using GEOSAT Altimeter Data

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ABSTRACT

Estimates of surface geostrophic zonal flow in the equatorial Pacific are deduced from the 17-day exact repeat orbit GEOSAT measurements for the period November 1986-November 1987. This period coincides with the height of the 1986-87 ENSO. Along-track altimeter height anomalies are first smoothed using a combination of linear and nonlinear filters. By combining several tracks in the zonal direction and filtering in time, we are able to obtain low frequency sea surface height at any point of the tropical Pacific. Currents are calculated from the differentiated form of the meridional momentum equation at the equator and from the classical first derivative of the meridional pressure field away from the equator. Comparisons of low frequency near-surface zonal current directly measured from equatorial moorings at 165°E, 140°W and 110°W yield a correlation of 0.83, 0.84 and 0.50 respectively with a mean rms difference of 0.23 m.s^{-1}. Sea level and zonal velocity solutions from a tropical Pacific numerical model are used as proxy data sets in order to quantify errors induced to quantify the geostrophic calculation by the GEOSAT space-time sampling.

In December 1986, a downwelling equatorial Kelvin wave is generated in the western Pacific and shows up, near the forcing area, as an intense local 1 m.s^{-1} eastward equatorial surface flow anomaly. This Kelvin wave propagates into the eastern equatorial Pacific with a phase speed of about 2.5 m.s^{-1} and is associated with eastward equatorial current anomalies of 0.3-0.5 m.s^{-1}. In February 1987, an upwelling equatorial Kelvin wave is excited near the date line and propagates eastward. This wave, characterized by a westward flow anomaly of 0.3-0.8 m.s^{-1}, reaches the eastern Pacific boundary in March 1987 where it forces apparently an upwelling first meridional mode equatorial Rossby wave. This Rossby wave propagates westward in the ocean interior at about 0.8 m.s^{-1} as a patch of equatorially trapped eastward flow (0.6-0.8 m.s^{-1} maximum) flanked, in both hemispheres, by 0.2-0.4 m.s^{-1} westward flow anomalies which decreased the South Equatorial Current and the North and South Equatorial Countercurrents. The equatorial Rossby wave propagation could be traced sequentially through the eastern, central and western Pacific from April to September 1987. Thus GEOSAT altimeter data indicate that equatorial Kelvin waves and possible eastern reflection as equatorial Rossby waves are an important component of basin scale surface current variability during the 1986-87 ENSO.

1. Introduction

One of the principal advantages of satellite oceanography is the potential for global monitoring of geostrophic ocean circulation and its variability. In the tropics, detection of current variability is complicated by stringent observational accuracies for

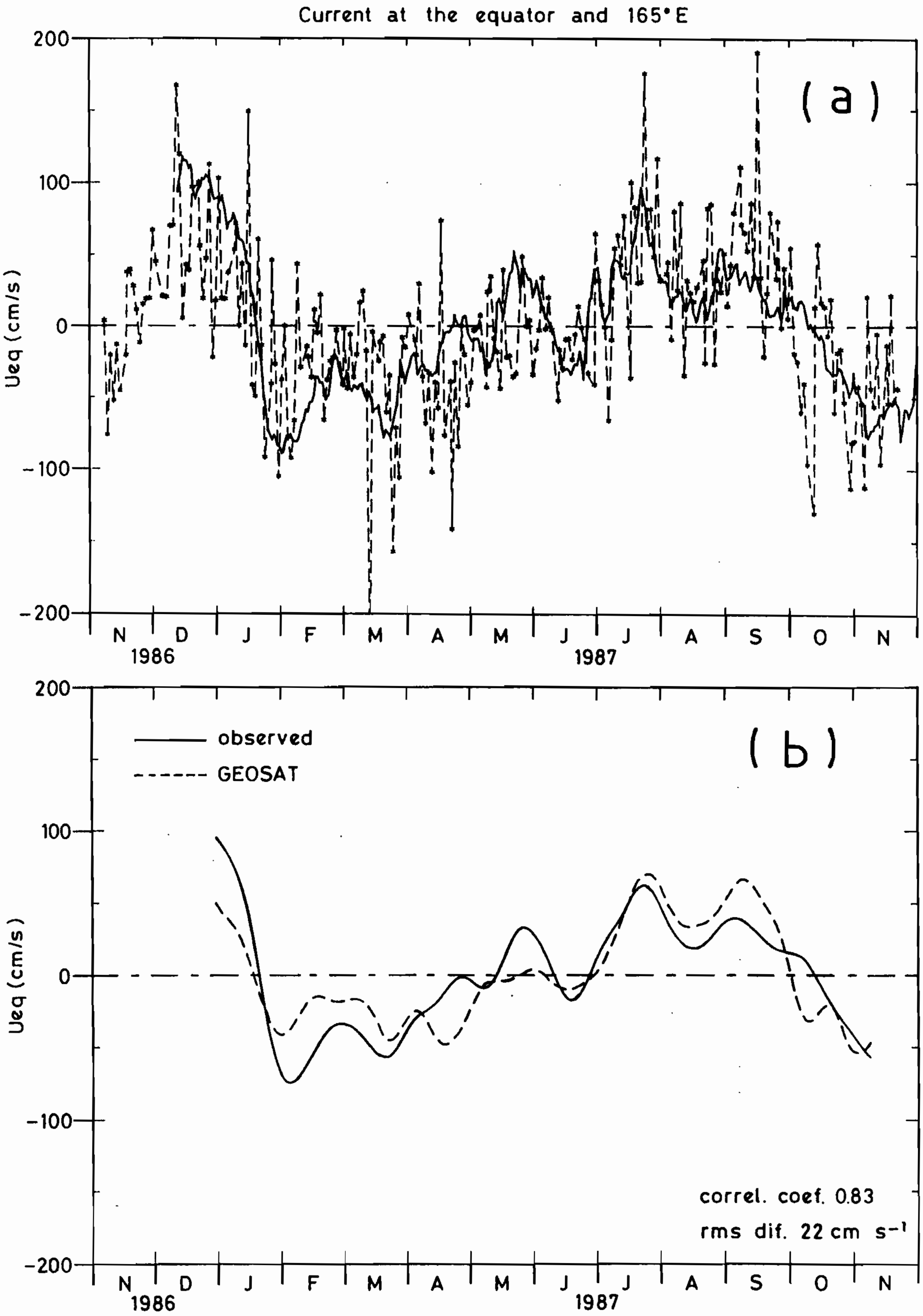

FIG. 1. Geostrophic zonal flow estimated from GEOSAT altimeter data (dashed line) and daily averaged near surface zonal flow measured directly from an equatorial mooring at 165°E (solid line). a) daily mooring time series and 1.5 day GEOSAT time series, b) time series low pass filtered with a 31-day Hanning filter.

estimating geostrophic currents because the horizontal component of the Coriolis force tends to zero. In a recent paper, Picaut et al. (1989) were the first to show that, based on comparisons with in situ data and a specific processing of GEOSAT sea surface heights, it is possible to obtain relatively good estimates of low frequency geostrophic zonal velocity at the equator from altimeter measurements. In this note, we summarize this paper and extend the geostrophic current technique calculation to the entire tropical Pacific. The present work is an useful complement of the GEOSAT sea level anomaly study of Delcroix et al. (1989; this volume, hereafter defined as DEP) since it mainly shows that, over the November 1986-November 1987 ENSO period, Kelvin waves and probably reflected Rossby wave are a dominant source of variability of the major surface equatorial currents.

2. Data processing and current intercomparisons

The GEOSAT data (Cheney et al., 1987) and its additional processing is succinctly presented in DEP and is detailed in Picaut et al. (1989). In the present study, the data correspond to the first 22 cycles of the 17-day Exact Repeat Mission (ERM) covering the period November 8, 1986 to November 18, 1987. At first, instrumental and oceanic small scale noise are filtered from along-track sea surface heights, using a combination of nonlinear and linear filters. Then all the ascending and descending tracks within 10° longitude band are combined together in order to reduce the original GEOSAT 17-day time step (down to 1.5 day right at the equator). Finally, high frequency temporal variability is suppressed from the resulting sea surface height time series with a 31-day Hanning filter. This processing results in a 3-dimensional GEOSAT sea level anomaly (GSLA) grid (0.5°latitude X 10°longitude X 5 days) over the tropical Pacific for the November 1986-November 1987 period.

The geostrophic zonal currents are then calculated from the sea level anomaly η and finite derivative schemes, outside the equator using the classical geostrophic equation:

$$f.u = -g.\eta_y \qquad (1)$$

and right at the equator using its meridional derivative on a β plane (Jerlov, 1953)

$$\beta.u = -g.\eta_{yy} \qquad (2)$$

For the specific current intercomparisons study of Picaut et al.(1989), the sequence for applying the second derivative equation is different from the previous one, since it is done immediately after the along track filtering. The results are very similar since the remaining processing (finite derivative, data grouping within 10° band and temporal filtering) are mainly linear. In that study, comparison of low frequency calculated and observed zonal currents, from equatorial moorings at 165°E, 140°W and 110°W, yields correlations of 0.83, 0.85 and 0.51, respectively with a mean rms difference of 0.23 $m.s^{-1}$. Figure 1 illustrates such intercomparisons at 165°E between non-filtered and filtered zonal currents. At 110°W, the inconclusive correlation is due to the lack of descending tracks around the mooring site (Cf. Fig. 1 in DEP). Finally, in the intercomparisons study, a discussion of errors existing in the geostrophic calculation at the equator is presented using sea level and zonal velocity solutions from a tropical Pacific numerical model as proxy data sets.

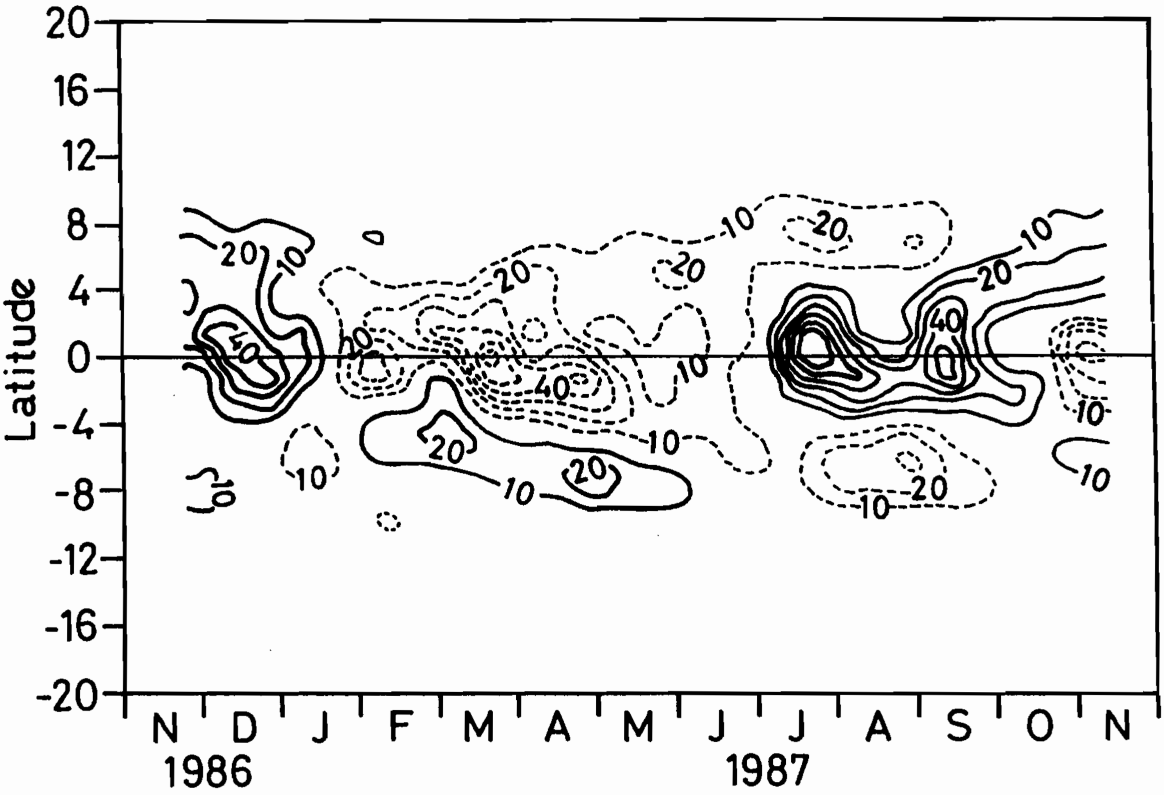

FIG.2. GEOSAT zonal current anomalies (cm.s^{-1}) as a function of time and latitude, along the 165°E longitude.

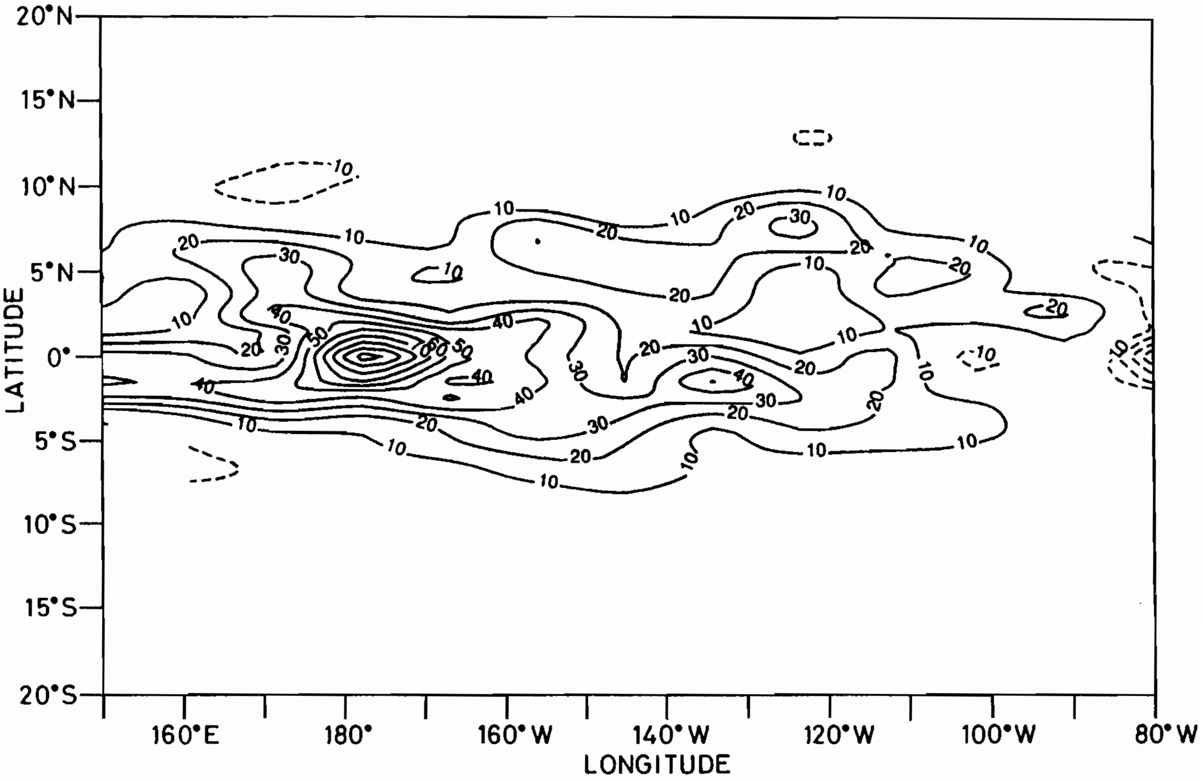

FIG.3. GEOSAT zonal current anomaly (cm.s^{-1}) signature of the downwelling Kelvin wave on January 5, 1987.

3. Surface current variations in the tropical Pacific

DEP have focused on the major GEOSAT sea level anomaly (GSLA) equatorial patches along 165°E and have shown that most of them could be interpreted as equatorial Kelvin and Rossby waves. Similarly, we now present the corresponding GEOSAT zonal current anomalies (GZCA). Similar to the GSLA study, one must keep in mind that the GZCA are relative to their mean over the November 1986-November 1987 period. A discussion of a directly measured currents at 0°, 165°E, and their relation to local wind forcing during the 1986-87 ENSO, is presented in McPhaden et al. (1989).

Figure 2 represents GZCA along the 165°E longitude, as a function of time and latitude. This figure shows that surface current anomalies are unimportant poleward of 10° and are mostly trapped to the equator. The strongest zonal current variations appear at the equator and are very similar to the observed variations depicted in figure 1. From this latter figure, we note that the rms difference between the observed and calculated current is 0.22 $m.s^{-1}$ which implies that, at the equator, GZCA are questionable when smaller than this value. Outside the equator, and due to the 1/f ratio in Eq. (1), the zonal current uncertainty is smaller than at the equator. This ratio 1/f is also the reason why the currents are generally trapped to the equator. This is clearly evident on figure 3 which represents the current structure associated with the downwelling Kelvin wave, generated in November-December 1986 in the western Pacific (Miller et al., 1988). Near the wind forcing area (Cf. Fig.5 in DEP), the eastward equatorial current goes up to 1 m s^{-1}. Then the equatorially trapped current structure (0.3-0.5 $m.s^{-1}$ maxima) propagates into the eastern equatorial Pacific at a phase speed of about 2.5 $m.s^{-1}$ (Fig.4). This figure also shows evidence, in the surface current from February to March 1987, for the generation and propagation of the equatorial upwelling Kelvin wave as noted in DEP. Referring back to figure 2, we note that the last notable current structure anomaly occurs in July-September 1987, along the 165°E longitude. This structure appears as a large equatorial eastward flow anomaly up to 0.6 $m.s^{-1}$ associated on the northern and southern sides by two westward flow anomalies down to -0.2 $m.s^{-1}$. According to DEP, the corresponding GSLA patch has the meridional structure of a first vertical first meridional equatorial Rossby wave.

In contrast to an equatorial Kelvin wave, the theoretical profile of zonal currents associated with an equatorial Rossby wave is far different from its sea level representation (e.g. Fig.9 in DEP). As noted above, it appears as a strong equatorially trapped current flanked in both hemispheres by two opposite currents of smaller amplitude. Such equatorial Rossby current structure is more evident in the eastern and central Pacific than in the western Pacific. Figure 5 illustrates such observed meridional current structure at 145°W and its least square fit to the theoretical first meridional Rossby wave function:

$$U(y) = U_0\, 2^{-3/2}\, \pi^{-1/4} \left(-3/2 + \beta y^2/c \right) \exp\left(-\beta y^2 / 2c \right)$$

The associated Kelvin wave speed c corresponds to 2.7 $m.s^{-1}$, i.e. the first vertical mode. Theoretically the first meridional equatorial Rossby wave propagates westward at a phase speed equal to c/3. Figure 6 represent the time/space sequence when the Rossby wave is most evident in the current structure. The equatorially trapped current anomaly (0.5 to 0.8 $m.s^{-1}$ maximum), accompanied by the northern and southern westward current anomalies (-0.2 to -0.4 $m.s^{-1}$ maxima), propagates between April 15 to June 1 from the eastern to the central tropical Pacific at a mean phase speed of 0.8 m s^{-1}. This propagating current structure is no longer evident between 150°W and the date line but

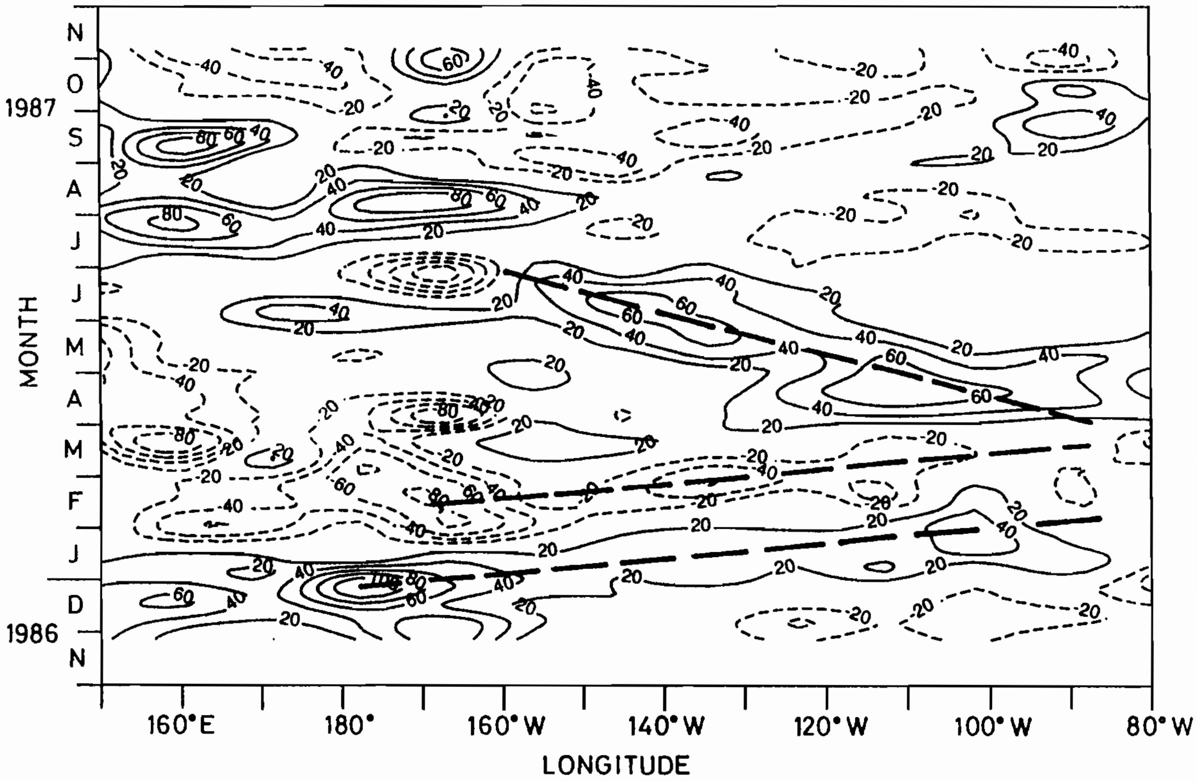

FIG.4. GEOSAT zonal current anomalies (cm.s^{-1}) along the equator as a function of time and longitude. Heavy broken lines indicate the propagation of equatorial Kelvin and Rossby waves.

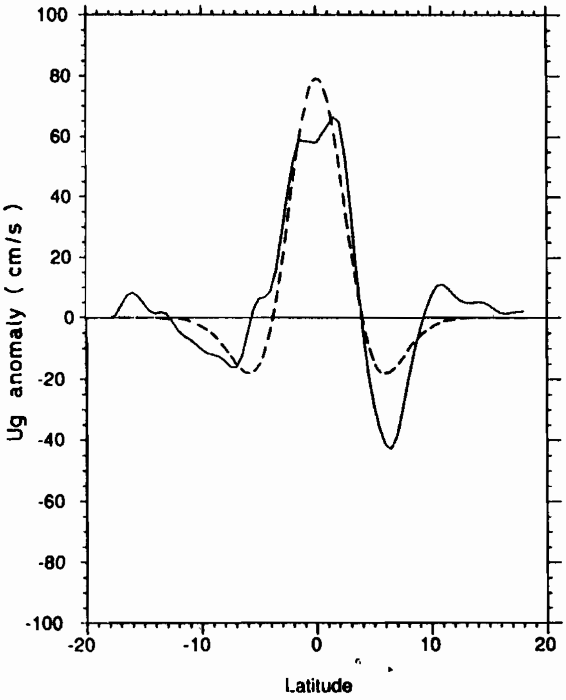

FIG.5. Meridional GEOSAT zonal current profile along 145°W in June 1, 1987(solid line). The dotted line corresponds to the least square fit of the theoretical zonal current associated with the first meridional equatorial Rossby wave.

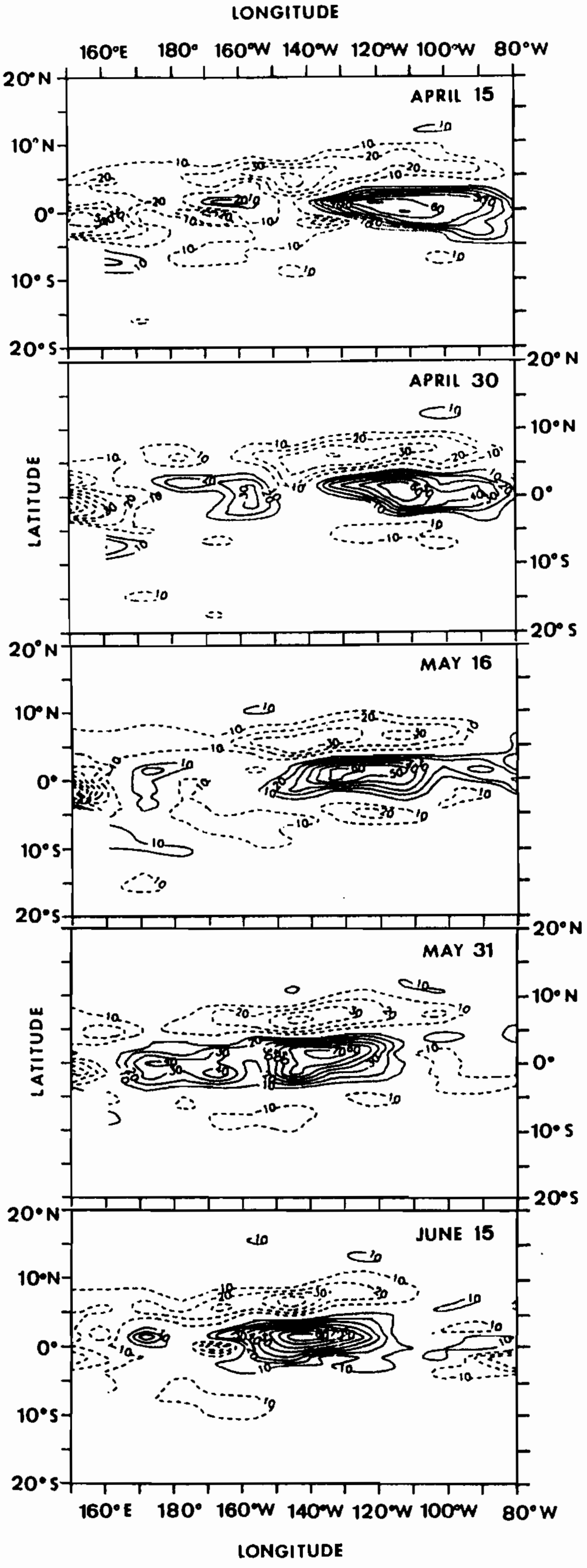

FIG.6. Time/space representation of the GEOSAT zonal surface current (cm.s^{-1}) from April 15 to June 15, 1987. It evidences the westward propagation of the equatorial upwelling Rossby wave from the eastern to the central tropical Pacific.

reappears around 165°E (Figs.2 and 4). Between the gap the equatorial Rossby wave GZCA is probably blurred by other equatorial phenomena or imprecise GEOSAT data (Cf. Fig.1 in DEP).

4. Discussion and conclusion

In this note we first summarize the study of Picaut et al. (1989) who have shown that, based on comparisons with in situ current data at three sites in the Pacific Ocean, it is possible to make physically meaningful estimates of surface geostrophic zonal velocity variations at the equator using GEOSAT data. The high correlations and relatively small rms at 165°E and 140°W is surprising when one considers that a 1 cm error in sea level, if uncorrelated over 1° latitude on which the present geostrophic flow is computed, would lead to errors of 0.7 $m.s^{-1}$. The success of such a computation is due to the accumulation of several factors such as the efficiency of the filtering technique, a current decorrelation scale in the meridional direction that is probably much greater than our grid size, and a zonal decorrelation scale of low frequency zonal current variations large enough to justify the combination of all ascending and descending tracks within each 10° longitude band. Since the computation of geostrophic zonal current is more sensitive to noise contamination at the equator than at higher latitude it has been possible to extend the geostrophic calculation with GEOSAT data to the entire tropical Pacific ocean.

Over the November 1986-November 1987 period of available GEOSAT measurements, we have shown that zonal surface current variability in the tropical Pacific are substantially influenced by two types of surface current structures. The first one corresponds to a downwelling (or upwelling) equatorial first vertical mode Kelvin waves which is characterized by an eastward (or westward) equatorially trapped zonal flow anomalies. These anomalies can reach 1 $m.s^{-1}$ near the forcing area and decrease to less than 0.5 $m.s^{-1}$ further east. The second current structure corresponds to a first meridional, first vertical, equatorial upwelling Rossby wave. It is composed of an equatorial eastward flow of 0.5-0.8 $m.s^{-1}$, flanked on the northern and southern sides by two westward flows of 0.2-0.4 $m.s^{-1}$. From the first panel of figure 6 it seems that this Rossby wave emanates from the eastern boundary of the tropical Pacific and figure 4 indicates that it could be due to the reflection of the upwelling equatorial Kelvin generated near the date line in February 1987. Because of their amplitude and propagating nature, these equatorial Kelvin and Rossby wave current structures strongly influence the variability of the South Equatorial Current and the North and South Equatorial Countercurrents over most of the tropical Pacific. The GEOSAT ERM data used in the present study does not precede or extend beyond the 1986-87 ENSO period. Therefore it is not possible yet to determine if the equatorial wave current structures we observed are prevalent in a normal years as well.

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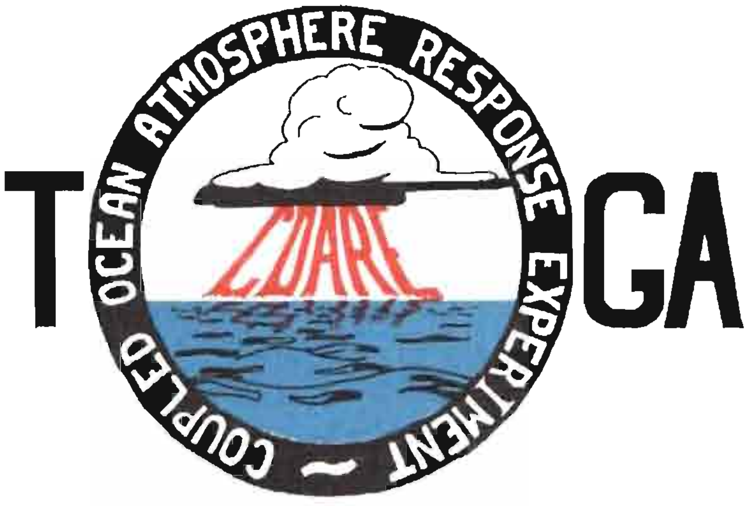

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