Instability Waves in the Tropical Pacific Observed with GEOSAT

Claire PERIGAUD

Jet Propulsion laboratory, MS 300/323
4800 Oak Grove Drive
Pasadena, CA 91109, U.S.A.

ABSTRACT

Sea level variations for periods between 20 to 50 days are examined in the tropical Pacific ocean from Geosat data which have been processed and analyzed weekly during the first 13 months of the Exact Repeat Mission. Based on comparison with twice daily tide-gage data, sea level variations can be determined with an rms accuracy of 6 cm for time scales of a week. Subsampling by the satellite and smoothing introduced by the analysis aliase the frequency spectra by introducing artificial secondary peaks and reducing the energy level of significant peaks. However the synopticity of the satellite observations give significance to the energy peaks detected locally and allows a detailed description of the 20 to 50 days oceanic variations during 1 year. Along the equator, sea level spectra show low energy. The highest energy is found in the Northeastern Pacific along 5ºN for 25 to 45 day periods, 1000 to 1500 km wavelengths, and a westward 40 km/day phase velocity. The signal filtered in this band of wavelengths and periods shows the strongest amplitude East of 160ºW and the weakest amplitude along 2000 km in the Central Pacific. Waves are propagating energy eastward and are seasonally modulated in high correlation with the shear-strength of the zonal flows. West of the central zone of minimum amplitude however, the signal is no longer well correlated with the shear-strength variations. The signals at 5ºN and 5ºS are not antisymetric with respect to the equator but positively correlated.

I INTRODUCTION

Instability waves have been observed and simulated as wavelike oscillations in the meridional velocity along the equator and in the sea surface temperature about 2º north of the equator in the Northeastern tropical Pacific. Weisberg (1987) provides a synopsis of their theoretical and observational history. These oscillations are narrow-band in frequency and wavenumber with time and zonal length scales centered about 30 days and 1000 km respectively. Their phase speed is westward and their apparent group velocity is eastward. These characteristics fit the Rossby-gravity wave ones. The pressure field of such a theoretical wave is antisymetric with respect to the equator. Maximum of wave amplitude in the dynamic topography has been observed in the Northeastern tropical Pacific with inverted echo sounders (Miller et al, 1985) and with Seasat altimeter data (Malarde et al, 1987). The packet duration of these oscillations is seasonnaly modulated and these waves seem to be generated by the (zonal or vertical) shear instabilities of the zonal equatorial currents (Cox, 1980). It seems clear that these instability waves play a primary role in the momentum balance of the near surface near equatorial mean currents. It is suggested that they may have similar importance for the near surface heat balance through meridional heat convergence towards the equator (Hansen and Paul, 1984).

The generation and decay of these energetic oscillations and the relation of their spatial and temporal distributions with the variations of the equatorial currents are addressed in this work. The Geosat altimeter data from the first year of exact repeat mission are processed and analyzed in the 20º band across the Pacific. Results are validated by

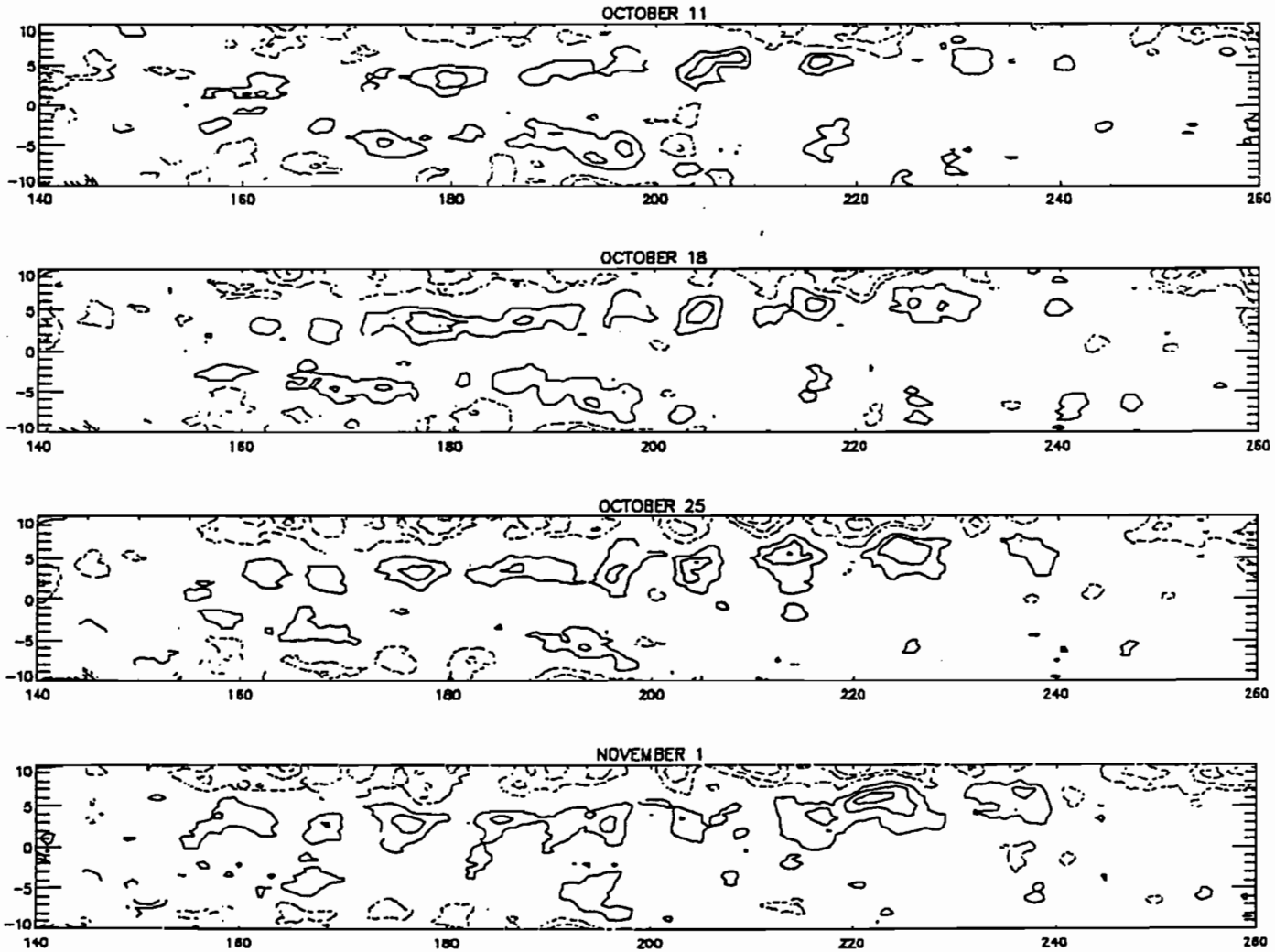


FIG.1. Weekly maps of sea level anomalies (relative to the 13 month mean) analyzed from GEOSAT altimeter data. Isocontours are 5 cm with continuous lines for positive and dotted lines for negative values. Zero contour is not drawn for more clarity.

comparison with tide-gage data. Frequency-wavenumber spectra are given as a function of latitude and altimeter signal filtered at the wave energy peaks is examined.

II ALTIMETER DATA PROCESSING AND ANALYZING

The Geophysical Data Record computed by NOAA's National Geodetic Survey (Cheney et al, 1988) are corrected for earth and ocean tide, inverse barometer response of sea level to atmospheric pressure, wet (FNOC) and dry tropospoheric path delays. Spikes are eliminated and data are gridded as a function of latitude along repetitive tracks of one ground "pass". Orbit errors are then corrected by applying to each repeat of each pass, a second degree polynom between 20ºS and 20ºN, using the mean of the differences to the most complete pass (as used in Zlotnicki et al, 1989). The mean is taken from November 8 1986 to December 20 1987 (first 24 cycles).

Residual orbit error is negligible over a narrow latitudinal band as studied here. Presence of wet tropospheric signal is surely effective in the tropical band (Emery et al, 1988). However, little contribution of this signal is expected in the range of wavelengths, periods and propagation speeds typical of the oceanic variations that are investigated in the present study.

Residual alongtrack altimetric differences are then analyzed using a successive correction method, as formerly used in meteorology (Tripoli and Krishnamurti, 1975). The spatial resolution chosen is d= 0.5 degree in latitude and longitude. This fine resolution results from a choice between the satellite crosstrack sampling (between 0 and 170 km at worst) and alongtrack sampling (7 km). The correlation function used in space is the Cressman function:
$(r^2-R^2)/(r^2+R^2)$ where r is the distance between the data point and the analyzed point and R is the correlation distance. Different sets of values for R have been chosen ranging from (4d, 3d, 2d, d) to (8d, 6d, 4d, 2d). An influence time of 34 days and an e-folding time of 5 to 7 days are applied on the weekly analyses performed over the 13 months of data. The time resolution (7 days) is chosen better than the satellite repetitive period (17 days) because oceanic information can be gained from neighbouring tracks within the satellite subcycle (3 days) This analysis is not optimal. It does not impose a westward phase speed as done with optimal analysis in (Malarde et al, 1987), nor any dynamical constraint as done with Kalman filter in (Gaspar and Wunsch, 1989). The present method certainly can be improved when the knowledge about the kinematics and physics of these waves becomes better.

A series of the sea level anomaly maps resulting from the Geosat analysis is presented in autumn 1987 (figure 1) showing succession of positive anomalies in the 3ºN to 8ºN latitudinal band. Some of them can be followed to migrate westward from week to week. Indeed the axis along which the anomalies are aligned, is not purely zonal but has a prevailing southwest-northeast orientation as has the axis of maximum shear-strength between the North Equatorial Counter Current and the South Equatorial Current (Kendall, 1970). However it is difficult from these results to characterize the waves involved in those variations as the anomaly maps represent the sum of the short-term, seasonnal and interannual variations for this particular year. Taking monthly averages and spatial smoothing over 1º latitude and 4º longitude of these series allow us to recover the sea level variations that have been described for the year 1986-1987 (Cheney and Miller, 1987). The present series enhances the important contribution of the short-term events in the seasonal variations of the tropical Pacific Ocean. These short-term variations detected by the satellite are validated in the next section.

III COMPARISON WITH TIDE-GAGE DATA

Tide gage data have been provided by Klaus Wyrtki on four island sites in the Central Tropical Pacific. These are twice daily data from November 1 1986 till December

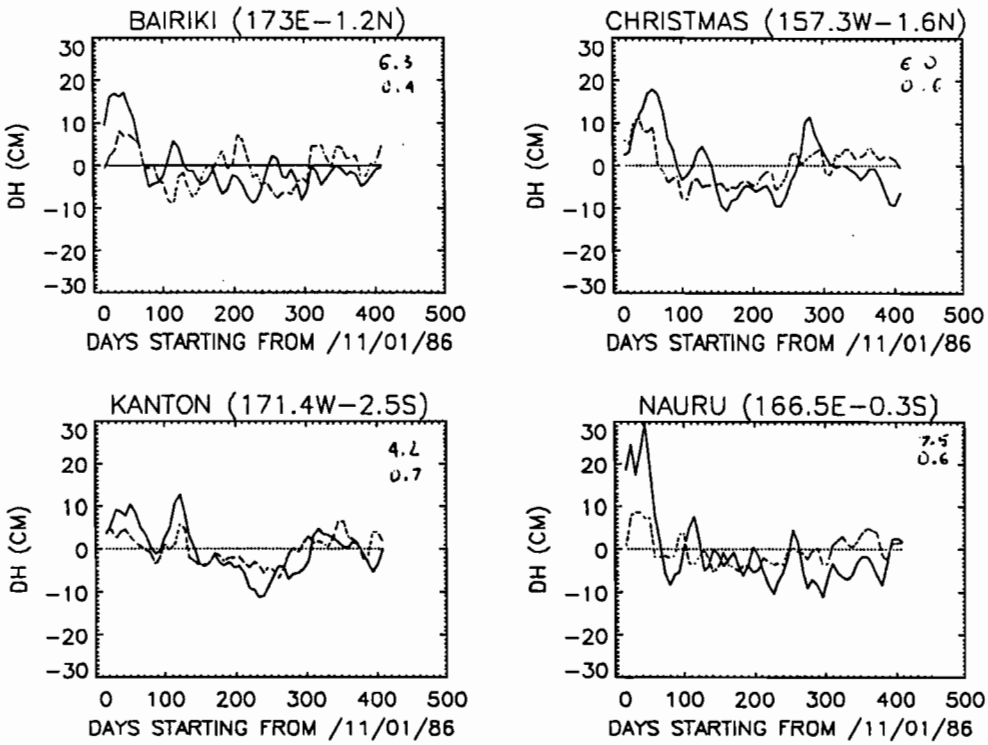


FIG.2. Variations of sea level relative to the 13 month mean derived from tide gage (continuous line) or from GEOSAT data (dotted line). The top value is the RMS difference between the 2 curves. The bottom value is the correlation coefficient.

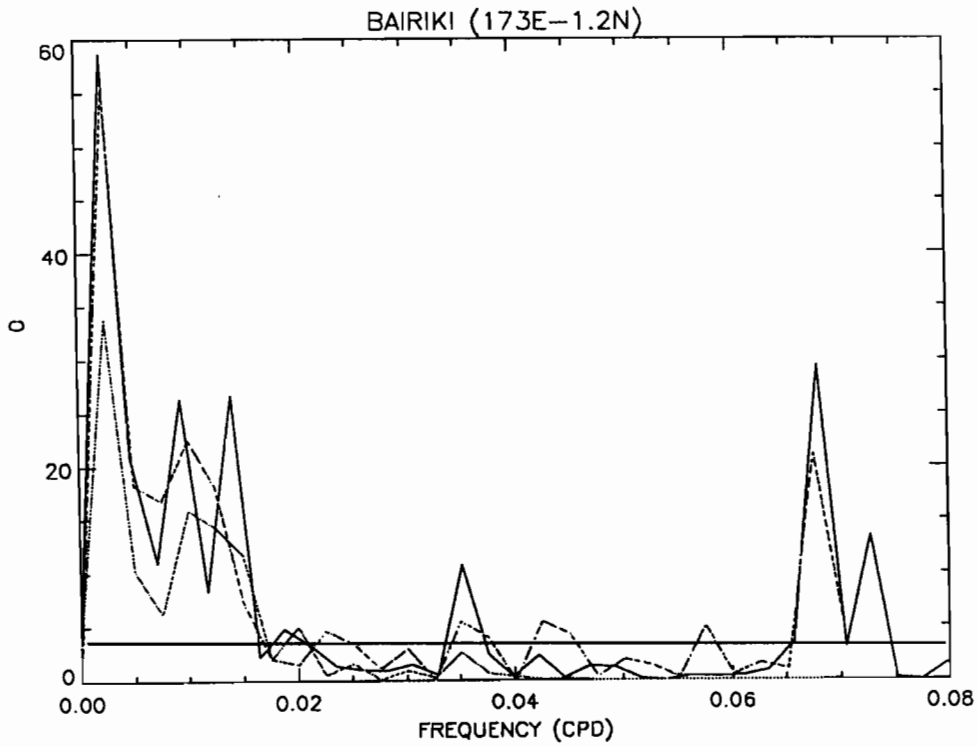


FIG.3. Frequency energy spectrum at Bairiki island derived from tide-gage data, with twice-daily data (continuous line), weekly subsampled data (dashed line) or 14 day averaged data (dotted line). The 95% level of confidence is given for the twice-daily data.

31 1987. The same 13 months mean is removed from these data and a 14 day running average is applied to remove the fortnight tidal signal. Then a weekly binning at the times corresponding to Geosat analyzed series is performed. The closest point within a 0.5 degree box around the island is extracted from the Geosat field for comparison. The time series (fig 2) agree within a mean RMS of 5.2 cm and a correlation coefficient ranging from 0.4 to 0.7. When the monthly mean is taken from both these series, the agreement is slightly better (mean RMS of 3.6 cm and correlation ranging from 0.1 to 0.8) and is a little less good than what Cheney et al (1989) found when comparing 16 sites of monthly averaged tide-gage data with Geosat over 18 months in 1985-1986 (respectively 3.7cm and 0.69). The energy spectrum of the non-smoothed non-subsampled tide-gage sea level presents 2 significant peaks at 14 days and 28 days. The former peak corresponds to a fortnightly tidal signal as found in Mitchum and Lukas (1987). The spectrum is modified by subsampling and smoothing (fig 3). Weekly subsampling twice-daily tide-gage data shifts energy from the higher frequencies into the lower ones so that artificial peaks show up in the 10 to 30 day range. Running a 14 day average on the twice-daily tide-gage data zeroes the fortnightly tidal signal but also reduces the 28 day signal just below the 95% level of confidence. These effects explain the differences between tide-gage and Geosat spectra (fig 4). Geosat peak has the energy level as the smoothed tide-gage peak, which has 50% less energy than the original one. Geosat spectra show secondary peaks between 10 and 30 days consistant with the subsampling aliasing. It is surely unfair to derive conclusions from these ponctual comparisons all the more as these islands happen to be in the Central Pacific where the variance is the smallest (Wyrtki, 1975). However Geosat series provide 300 grid points in longitude over which frequency spectra can be computed. Therefore the spatial consistency of the Geosat spectra can be examined.

IV WAVENUMBER-FREQUENCY SPECTRUM

Frequency spectra have been averaged in the Eastern (100ºW to 160ºW) and in the Western (140ºE to 160ºW) basins along zonal sections of the Geosat weekly series (fig 5). These basins have the same spectra along the equator, with a low of energy between 30 and 50 days, the highest energy level of all the spectra at the lowest frequencies and a secondary peak at 22 days just above the 95% level of confidence. The eastern basin presents significant peaks in the 25 to 45 day band both North and South of the equator. The peak maxima are centered on 33 days at 5ºN and 40 days at 5ºS and the secondary maxima centered at 7.5ºN and 7.5ºS with a wider frequency band shifted to the longer 40 day periods. The energy level is about twice larger in the North than in the South. The 25 to 45 day peak may be due to instability and will be studied in the next section.

The equator presents a minimum of energy in the 30 to 50 days as the Rossby-gravity wave has a zero sea level amplitude along the equator. The secondary peak at 22 day can be due to subsampling of the highest frequency waves which energy is concentrated in the equatorial wave guide.

In the western basin, significant peaks show up between 40 and 60 days but little energy is found below 35 days. The structure looks more complex than in the East and is certainly resulting from the superposition of different events. The increase in the periods from East to West has been observed in current measurements (Halpern et al, 1988) and tide-gage data (Chriswell and Lukas, 1989) and corresponds to the eastward dispersion of the Rossby-gravity wave. Two main differences appear between these spectra and those derived from 730 days of 17 tide-gage stations in the central and western 10ºS to 10ºN Pacific (Mitchum and Lukas, 1987). No 40 to 50 day peak is found along the equator and the 20 to 40 day peak is centered higher than 30 days rather than lower. The peak, which corresponds to sea level response to atmospheric oscillations (Enfield, 1987) may be absent on 1986-1987; indeed it has not either been observed in the Western Pacific Ocean for 1986-1987 (McPhaden et al, 1989).

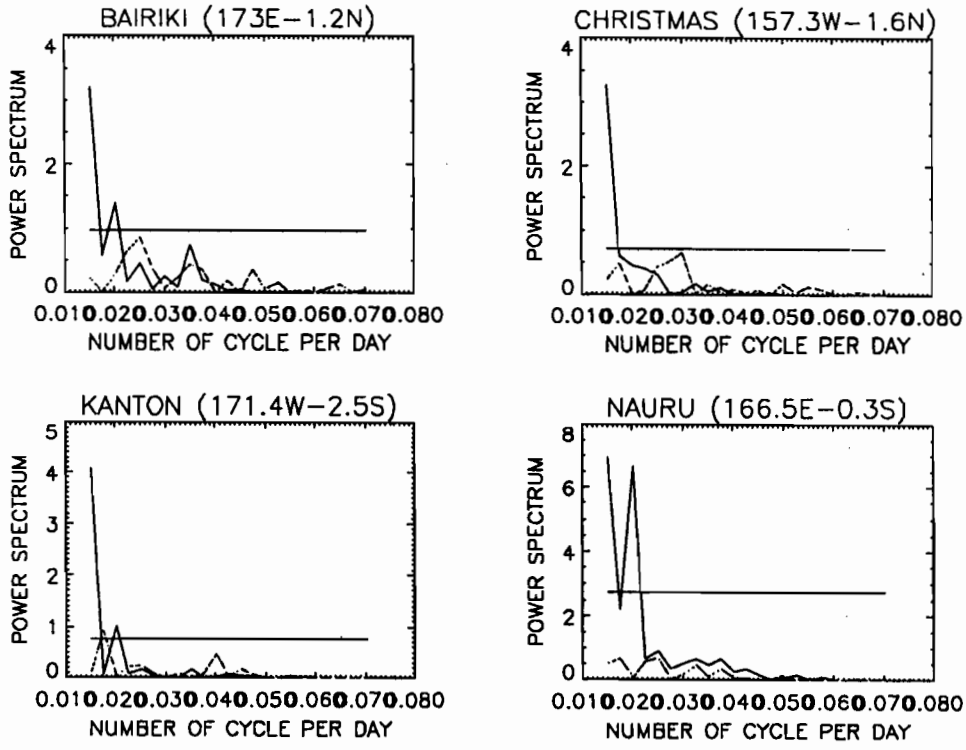


FIG.4. Frequency power spectra in cm²/cycle per day derived from tide-gage smoothed data (continuous line) and from GEOSAT data (dotted line). The 95% level of confidence is given for the twice-daily tide-gage data.

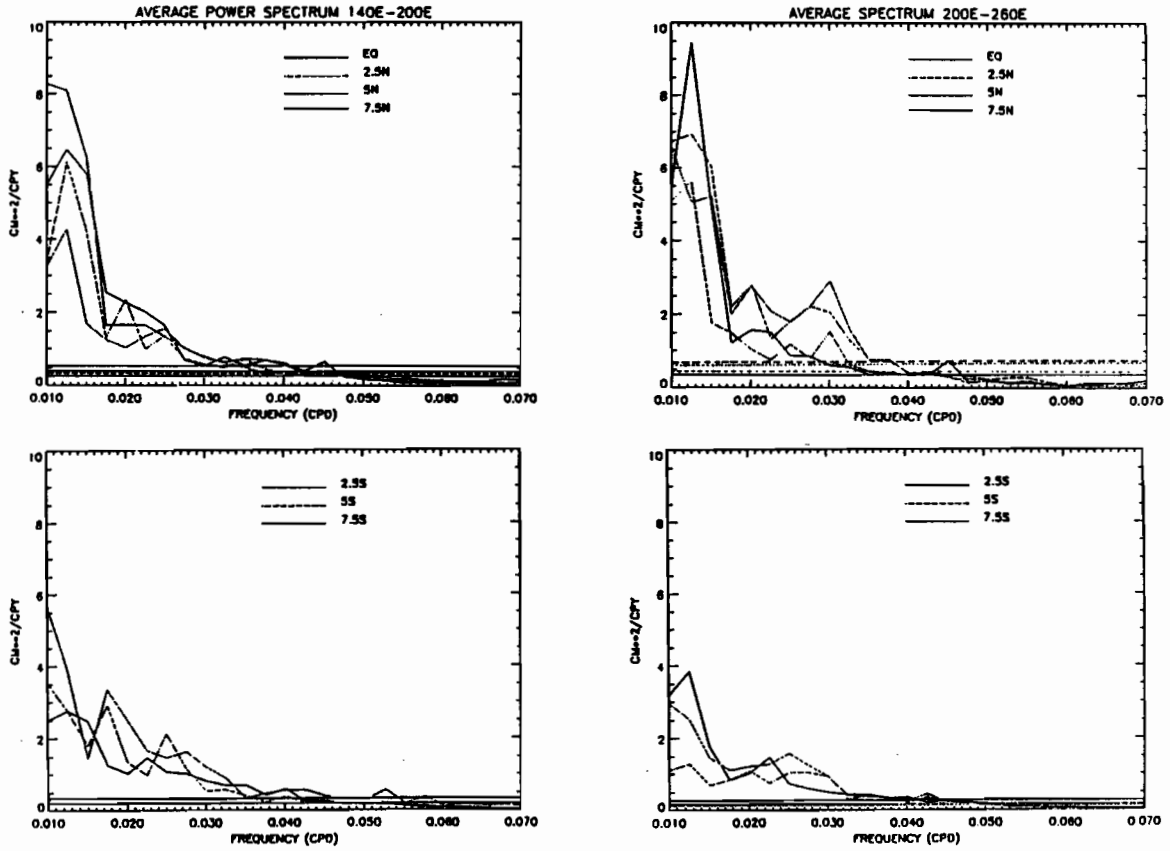
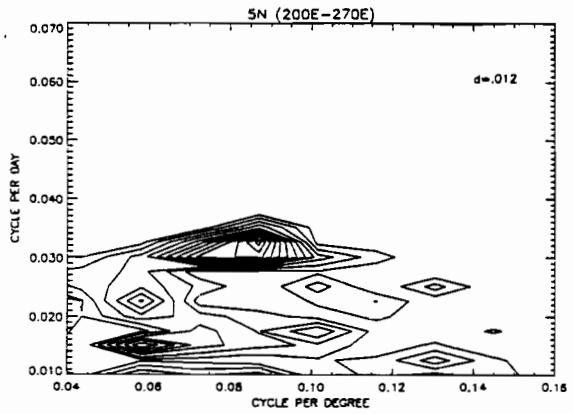


FIG.5. GEOSAT frequency power spectra averaged along zonal sections in the western and eastern Pacific. Units are cycle per day for frequencies and cm² per (cycle per year) for power.



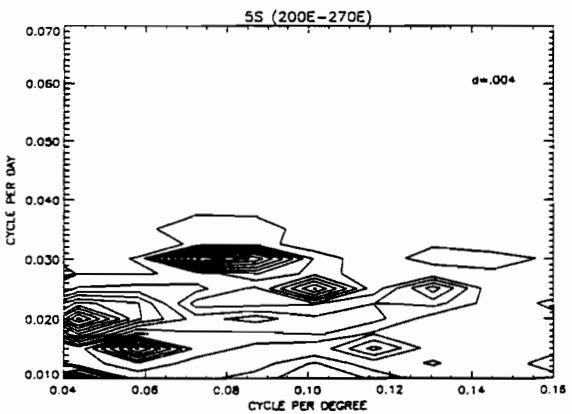


FIG.6. Wavenumber-frequency spectra derived at 5°N and 5°S zonal sections of GEOSAT anomaly maps. Units of isocontours are in cm^2 per (cycle per year) per (cycle per km).

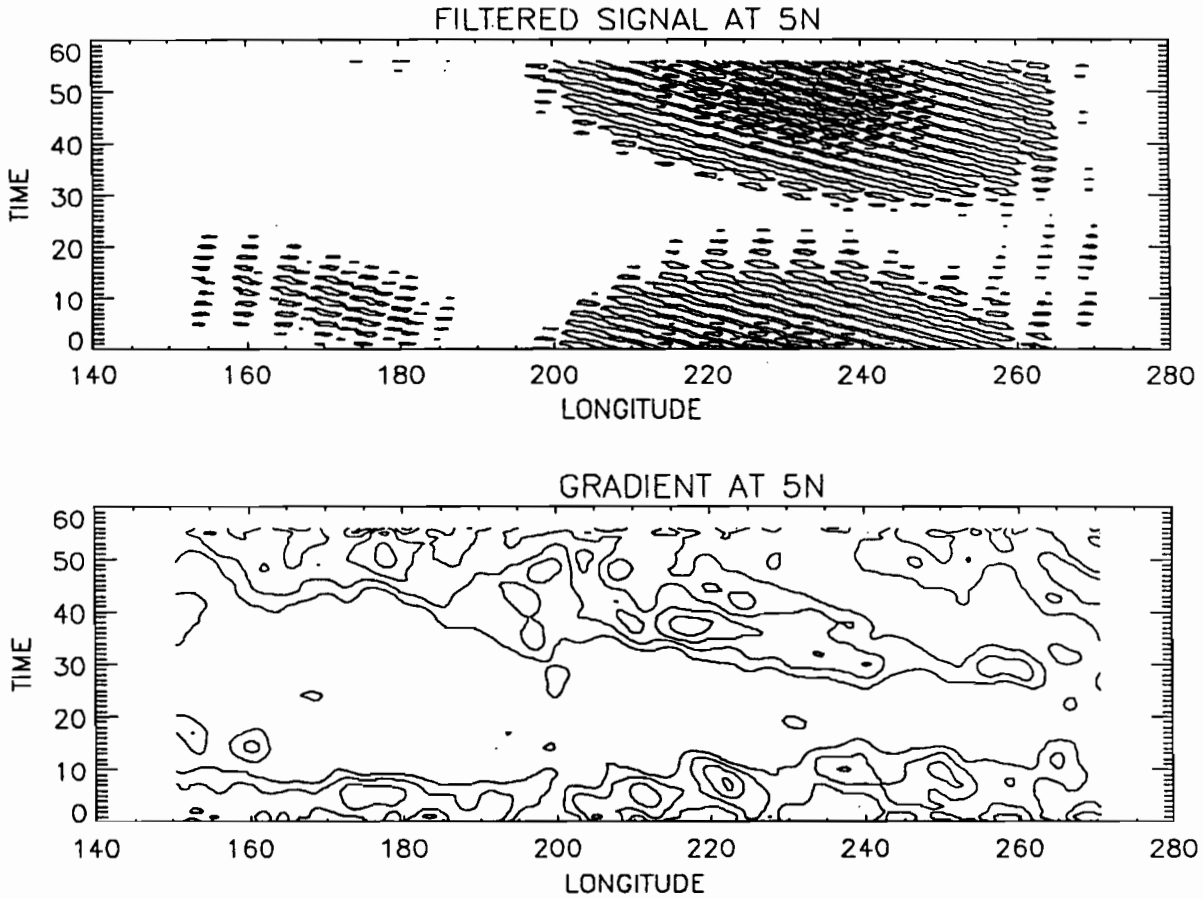


FIG.7. Top: Amplitude of GEOSAT filtered sea level variations at 5°N as a function of longitude and time (units of time axis are week starting on November 16 1986 and isocontours are 0.5 cm).

Bottom: meridional sea level gradient (relative to the 13 month mean): only the negative values increasing the shear-strength are contoured. Isocontour is 2 cm per degree of latitude.

Wavenumber frequency spectra are then given at 5ºN and 5ºS (fig 6). The 25 ot 45 day band corresponds to the 1000-1500 km zonal wavelength range. Some symetry relative to the equator is found as well in these wavelength band, but with less energy in the Southern than in the North.

V FILTERED SIGNALS

Geosat analyzed residuals are filtered within 25 to 45 days and 1000 to 1500 km. The filtered signal (fig 7 top) clearly shows a westward phase speed of 40 km/day. From November 1986 to February 1987, waves are present in the western and eastern Pacific with the strongest amplitude in the East and the weakest amplitude in the Central Pacific between 160ºW and 180º. The maximum amplitude in time is 4 cm East of 180º and 2 cm in the West. The eastern and the western packets of waves are disconnected. Waves are the weakest between February and June and become active again in the East from 120ºW in June to 160ºW in August. Very little wave activity is found in the West after February 1987.

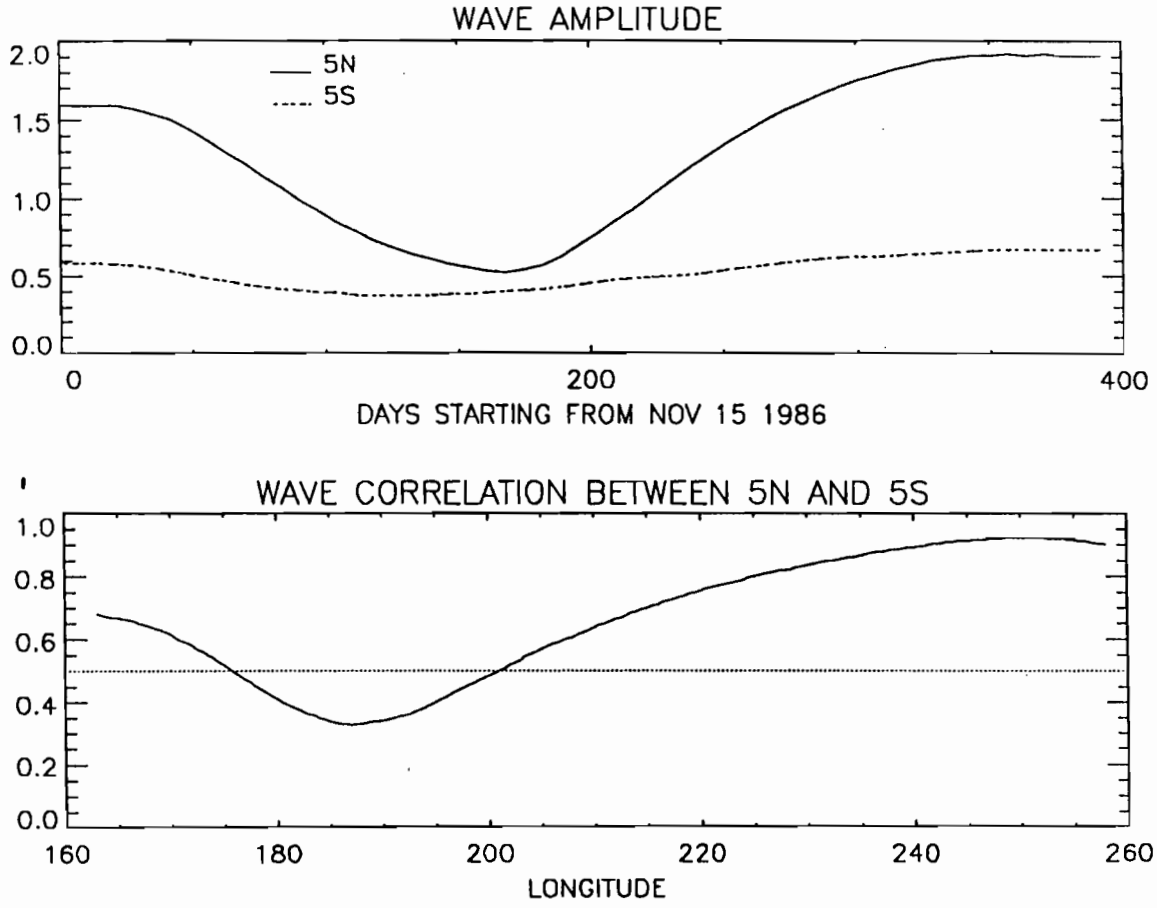


FIG.8. Top: Zonally averaged wave amplitude as a function of time.
Bottom: correlation in time between wave at 5°N and at 5°S as a function of longitude.

In the East, energy is transported eastward at 35 km/day. Furthermore the strong seasonal modulation is strongly correlated with the increase of shear strength between the South Equatorial Current and the North Equatorial Counter Current as measured by the meridional gradient of sea level derived from Geosat smoothed time series (fig 7 bottom). Indeed the axis along which the shear-strength increases in time by 2 cm per degree of latitude is tilted with time corresponding to a 40 km/day westward migration and its longitude-time location is well correlated with the strengthening of the waves as filtered above.

In the West, the phenomenon look different. The shear strength is increased in winter 1986-1987 when the waves are present but in summer 1987, the shear-strength continues to increase with time as in the East and the waves do not strengthen again before late 1987. Indeed 20 to 30 day oscillations of meridional velocity have been observed in the western Pacific in 1986-1987 with current measurements along the equator and have been correlated with meridional wind fluctuations (McPhaden et al, 1989).

The same filter in frequency and wavenumber has been applied along 5ºS. Then no clear eastward nor westward propagation of energy is found. The waves at 5ºS show similar seasonal modulation and longitudinal dependency (fig 8 top) but the correlation between 5ºN and 5ºS is always positive and shows significant symetry with respect to the equator (fig 8 bottom). The strongest signal in the North with a dominant symetry can be explained if the waves generated by instability are a superposition of Rossby-Gravity waves and Rossby waves. Similar mechanisms have been invoked in the superposition of Kelvin waves and Rossby waves (Busalacchi et al, 1983).

No evidence for Rossby-gravity wave nor link to the shear-current is demonstrated all across the Pacific. From figure 1 however, the positive anomalies are aligned all across the Pacific along the tilted axis of maximum sheared flow. The filtering zonally applied as previously precludes equatorial convergence of the waves (Schopf et al, 1981). This is why the same frequency-wavenumber band filtering has been applied within a 4º latitudinal band along a tilted axis. Then some energy is gained in the West compared to the previous results but the same time-longitudinal characteristics are found as well.

VI DISCUSSION

Geosat residuals have been analyzed with different space and time correlation parameters. The different Geosat analyzed series give similar mean RMS differences and similar range of correlation with the tide-gage data, although individual plots show significant differences with the previous ones. Nevertheless negligible difference is found in the spectra in the 10 to 50 day range, as well as in the filtered signal. Thus the previous results are not sensitive to the analysis parameters. This is consistent with the large zonal extent of the tropical waves. However the method used in this study is certainly not optimal to quantify the energy of the instability waves. Both the subsampling of the satellite and the smoothing of the analysis aliase the spectra. We must also keep in mind that water vapor content is not properly corrected in Geosat data and that the contribution of the atmospheric signal has not been examined in the present results.

With 13 months of Geosat data, it is possible to describe the time-longitude-latitude extent of the sea level anomaly due to instability waves. Waves with 1000-1500 km, 25 to 45 day, westward 40 km/day phase propagation and eastward 35 km/day energy propagation are clearly present along 5ºN East of 160ºW all year long except between February and June 1987. Compared to September 1978 as detected from Seasat altimeter (Malarde et al, 1987), these waves are less strong in September 1987. This is consistent with the weaker shear-strength present during the El-Nino 1986-1987 event. Furthermore, altimeter also provides the anomaly of shear-strength of the zonal flow. It is found that for the year 1986-1987, these waves are correlated with an increase of zonal shear East of the dateline and have a more complex latitudinal structure than the Rossby-Gravity wave.

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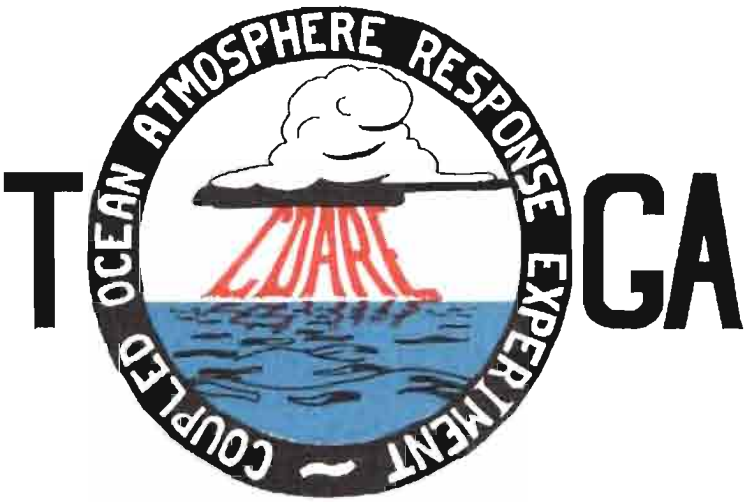

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