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Equatorial Sea Level Response During the 1982–1983 El Niño

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During the 1982–83 El Niño/Southern Oscillation event, sea level across the width of the equatorial Pacific adjusted to the reversal of the equatorial trade winds, and by the end of 1982 the normal sea level slope across the Pacific had been eliminated. The transfer of warm upper-ocean water from the western Pacific to the eastern Pacific was accomplished by a combination of direct wind forcing as the wind anomaly crossed the basin and by mass flux induced by free equatorial waves. The importance of equatorially trapped Kelvin waves of first and second vertical mode during the onset of the 1982–83 El Niño is inferred from the cross-correlation statistics between central and eastern Pacific sea level stations and between wind variations in the western Pacific and equatorial sea level stations to the east. The different propagation speeds of these two modes appears to be responsible for the observed change in shape of the major sea level signals during the 1982–83 event. Tentative evidence for first baroclinic mode, first meridional-mode Rossby waves is also presented.

1. Introduction

During 1982, the trade winds in the tropical Pacific weakened, eventually reversing direction so that the winds were blowing from west to east along the equator in the central Pacific. In response a zonal redistribution of water masses took place; sea level fell in the western Pacific and rose in the eastern Pacific. Strongest currents associated with this redistribution occurred in the upper layer above the thermocline, although anomalous currents were seen in and below the thermocline [*Firing et al.*, 1983; *Halpern et al.*, 1983]. Because of the contrast in temperature of the surface layer between the eastern and western Pacific, large temperature anomalies [*Rasmussen and Wallace*, 1983] were associated with this oceanic response to the anomalous winds [*Harrison and Schopf*, 1984].

For several years the working hypothesis for the onset of El Niño conditions in the eastern Pacific has been that the collapse of the equatorial trade winds in the western Pacific triggers equatorially trapped Kelvin waves that propagate along the equator to the coast of South America [*Wyrtki*, 1975*a*, 1977]. The first baroclinic mode waves take less than 2 months to cross the Pacific; higher modes take longer. The passage of these waves causes changes in the equatorial and coastal currents, and El Niño begins. The equatorial Rossby waves generated as part of the Kelvin wave reflection [*Moore and Philander*, 1977] propagate back into the interior, possibly causing further anomalous conditions.

Here we briefly describe some important aspects of the response of sea level in the equatorial Pacific Ocean to anomalous zonal winds during the 1982–83 El Niño. Then we present direct evidence of free equatorial waves in the central and eastern Pacific during the period prior to and including the onset of the 1982–83 El Niño.

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2. Data and Methods

Tide and subsurface pressure gauges recorded sea level variations at Nauru (0°32′S, 166°54′W), Christmas (1°59′N, 157°29′W), Jarvis (0°23′S, 160°W), Isabela (0°3′S, 91°28′W), and Santa Cruz (0°27′S, 90°17′W). The records were low-pass filtered to remove tidal variations, and then daily mean sea level was calculated. These time series (Figure 1) show the onset of the 1982–83 El Niño, which is indicated by the large and rapid increase of sea level during July 1982 in the central Pacific and by the slow rise in the eastern Pacific, beginning in August. Monthly mean sea levels were calculated from the daily values, and anomalies from the long-term monthly means at each site were derived. *Wyrtki* [1984] discusses further details of these calculations.

In addition, an index of equatorial zonal wind in the western Pacific was kindly provided to us by James Sadler of the University of Hawaii (Figure 1). This index consists of daily averages of the 6-hourly wind observations at Tarawa, Nauru (Ocean Island), and Beru (Arorae), all near 170°E. Observations from the islands in parentheses were used when the primary site did not report. The averaging of observations from sites north of, on, and south of the equator tends to emphasize signals in the zonal wind field that are symmetric with respect to the equator. The onset of persistent westerly winds in June 1982 is apparent, but note also the energetic high-frequency variations with periods of several days and the sporadic "bursts" of westerly wind [*Luther et al.*, 1983].

3. Wind Changes

According to *Sadler and Kilonsky* [1983], anomalous and persistent westerly winds began in May–June 1982 in the western Pacific, extending eastward to about 175°E, although several episodes of strong westerly winds had occurred much earlier and farther to the west. Subsequently, these anomalous westerlies moved eastward, eventually reaching the coast of South America in early 1983. This progression can best be seen in the time-longitude diagram of zonal wind anomaly at the 850-mbar level (approximately 1 km above the sea surface)

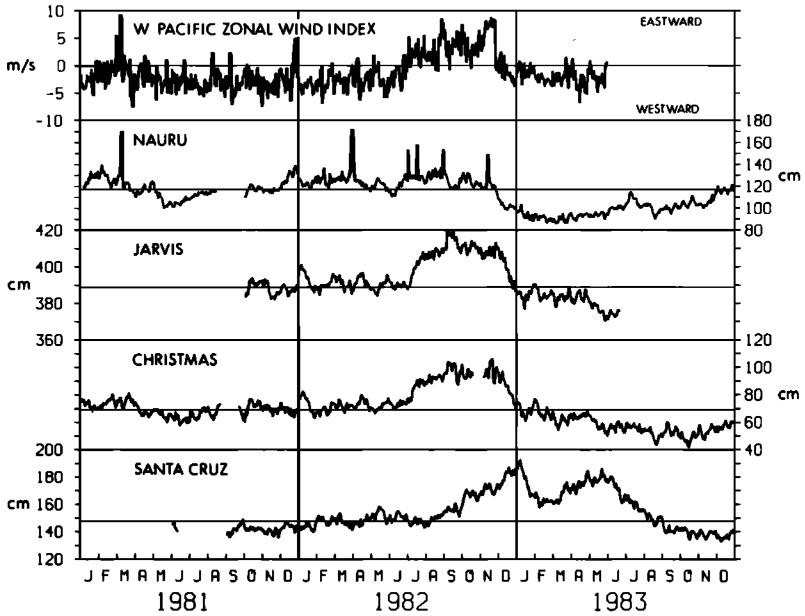

Fig. 1. Time series of daily mean zonal wind index for the equatorial Pacific near 170°E and daily mean sea level from near-equatorial Pacific island stations. Thin horizontal lines indicate long-term mean sea level relative to an arbitrary reference. The locations of the sea level stations and the construction of the wind index are described in the text.

published by *Gill and Rasmusson* [1983]. From the slope of the wind anomaly contours we estimate that the anomalous winds moved eastward at 0.4–0.5 m/s, although there was considerable synoptic variability, and much of the westerly winds occurred in eventlike bursts (see *Luther et al.* [1983] for a discussion of westerly wind bursts and their relationship to occurrences of El Niño).

4. Sea Level Response

To get a picture of the adjustment of the tropical Pacific to this anomalous forcing, *Firing et al.* [1983] superimposed the monthly mean sea level anomalies at several near-equatorial island stations across the Pacific on the mean dynamic topography of the sea surface relative to 500 dbar, as calculated from historical data by *Wyrtki* [1975*b*]. Their Figure 3 shows the resulting time-longitude distribution of near-equatorial sea level across the Pacific. The normal slope of the sea surface upward from east to west maintained by the persistent equatorial easterly trade winds is evident in early 1982. In June 1982, sea level rose at Nauru and began to fall at Rabaul. Sea level rose about a month later at Christmas Island and 3 months later at the Galapagos Islands. As sea level rose along the eastern boundary it started to fall at Nauru and Christmas. By January 1983 the sea level slope across the Pacific had been virtually eliminated.

The peak sea level anomaly moved across the Pacific at a

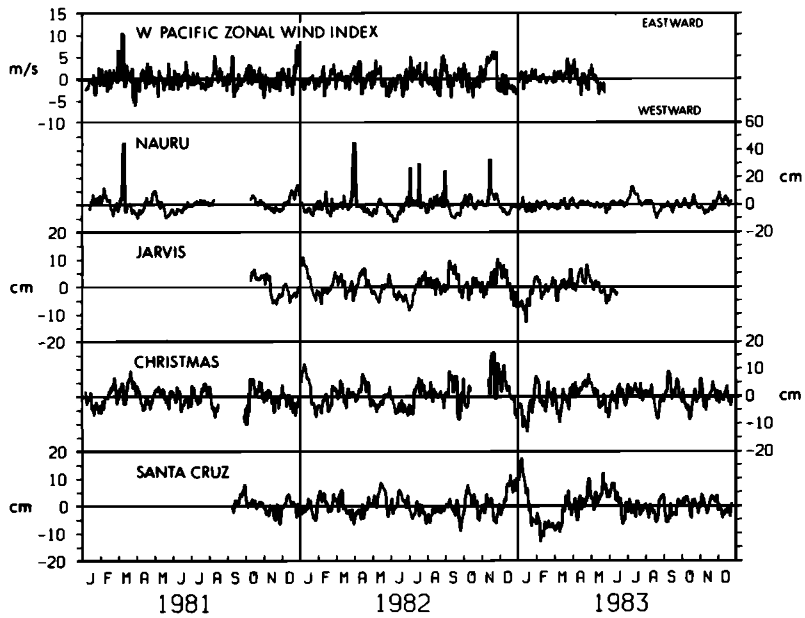

Fig. 2. Daily high-pass filtered western Pacific zonal wind index and sea level series of Figure 1. Filtering is described in the text.

TABLE 1. Wind-Sea Level and Sea Level-Sea Level Cross-Correlation Function Peaks Significantly Different From Zero at >90% Confidence

Record Pair	Dates	Correlation		Significance, %	Lag, days	Phase Speed, m/s
West Pacific wind/	October 4, 1981	0.40	4.74σ	99+	2	*
Nauru sea level	March 30, 1983	0.24	2.81σ	99+	−8	*
		−0.20	-2.30σ	98	29	*
		0.18	1.94σ	95	93	*
West Pacific wind/	October 4, 1981	0.41	4.07σ	99+	12	3.20
Jarvis sea level	May 31, 1983	−0.19	-1.85σ	93	−16	*
		−0.19	-1.82σ	93	56	0.69
West Pacific wind/	January 1, 1982	0.46	3.17σ	99+	45	2.85
Santa Cruz sea level	February 27, 1983	−0.27	-1.94σ	95	13	9.90
Jarvis sea level/	February 25, 1979	0.36	3.09σ	99+	28	3.21
Santa Cruz sea level	October 15, 1980					
	October 4, 1981	0.31	2.28σ	98	29	3.10
	December 31, 1982	0.27	1.97σ	95	56	1.61
		0.28	1.91σ	94	−84	−1.07
		−0.23	-1.76σ	92	8	11.24
Christmas sea level/	September 23, 1981	0.29	2.32σ	98	28	3.10
Santa Cruz sea level	October 19, 1982	0.29	2.20σ	97	58	1.50
		−0.26	-2.12σ	97	13	6.67
		0.25	1.80σ	93	−80	−1.08

Asterisks denote cases where physically meaningful phase speeds could not be calculated.

speed of about 1 m/s [*Wyrtki*, 1984], more rapidly than the wind anomaly discussed earlier. The peak in sea level preceded the onset of actual westerly winds at longitudes east of the dateline, though it is difficult to determine the relative timing of the onset from monthly mean data. Certainly, the peak in sea level preceded the maximum wind anomalies by a month or more at each station. Thus it seems that the anomalous sea level changes may be more closely associated with the suddenness of the onset of wind anomalies along the equator and the sharp zonal gradients of the anomalies.

Inspection of the daily mean sea level data (Figure 1) shows a qualitative difference in the sea level signal seen in the central and eastern Pacific. The rapid rise observed in the central Pacific is not seen in the relatively slow rise near the eastern boundary. We offer an explanation for this in the following section.

Finally, we point out the "event-like" sea level pulses common to the records. These have durations of 2–3 weeks and amplitudes of as much as 10–15 cm. An example is seen in the Jarvis Island record during September 1982. The pulses are related to the westerly wind bursts mentioned earlier [*Knox and Halpern*, 1982; *Luther et al.*, 1983] and may be important in the onset phase of El Niño events.

5. DYNAMICS

As a first step in understanding the dynamics of the oceanic response to the atmospheric forcing we calculated the cross-correlation function between the western Pacific zonal wind index and the equatorial sea level records shown in Figure 1. Subsets of the records were chosen to focus on the period of onset of unusual conditions, where it was thought that the dynamics might be simpler than during the mature phase of El Niño. These subsets were about 1 year in length, with the onset of El Niño (July–August 1982) approximately centered. The starting and ending dates are given in Table 1.

Correlations were calculated from the series of daily values, but the large anomaly in both wind and sea level has an inherently long time scale that reduces the significance of the cross-correlation statistics considerably. Also, the resulting broad peaks do not allow good resolution of the associated lags. Therefore the daily values were high-pass filtered with a Butterworth filter [*Roberts and Roberts*, 1978] to remove trends and other poorly resolved low-frequency variation, thus reducing the integral time scale [*Davis*, 1977; *Chelton*, 1982]. The cutoff period used was 180 days, and the time series were filtered forward and backward to eliminate phase shifts. These filtered series are shown in Figure 2. Correlations were then calculated between these filtered series and the results presented in normalized form [*Sciremammano*, 1979]. Here the vertical axes of the cross-correlation function plots are in units of standard errors of the correlation coefficients, taking into account the autocorrelation of the time series and the number of points actually used for each lag. Correlation coefficients are approximately normally distributed [*Sciremammano*, 1979], so a normalized cross correlation of 1.96 is significant at the 95% confidence level.

Figure 3 shows that the sea level variations near the equator across the Pacific are significantly correlated with zonal wind fluctuations in the western Pacific and that the wind leads central and eastern Pacific sea level. Because the tide gauge at Nauru is situated in a harbor that is exposed to the west, the local response to westerly wind events is enhanced (Figures 1 and 2), and the correlation between sea level and wind is quite high. Table 1 lists the correlations that are significant at 90% or greater and their associated lags. The lags at maximum correlation suggest a propagation speed of about 3 m/s, a speed that has been observed to be associated with first baroclinic mode, equatorially trapped Kelvin waves [*Knox and Halpern*, 1982; *Eriksen et al.*, 1983]. Of course, it is possible that zonal wind variations in the central and eastern Pacific were highly correlated at these lags with the western Pacific winds, but evidence suggests that the anomalous winds did not occur until September 1982 in the central Pacific [*Firing et al.*, 1983] and in early 1983 in the eastern Pacific

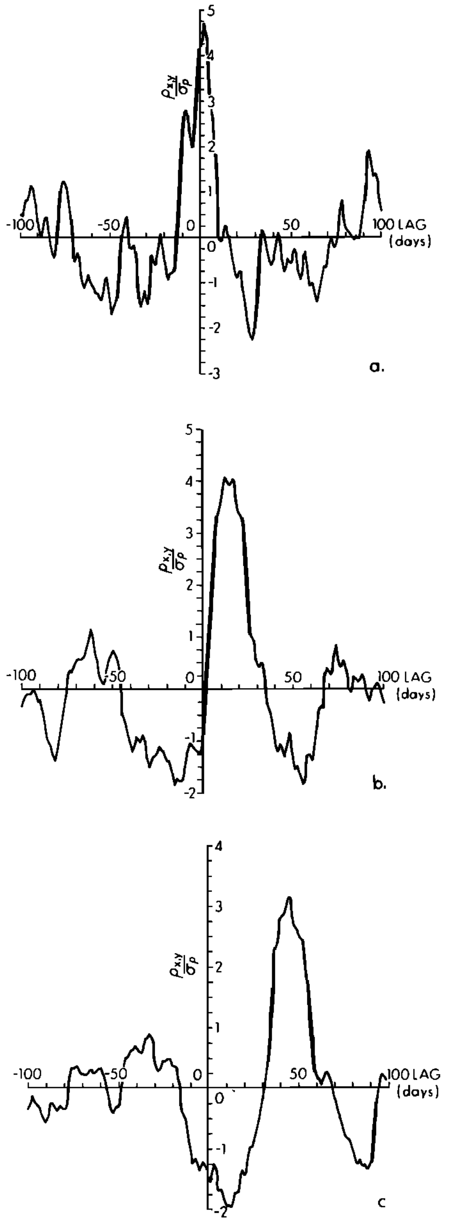

Fig. 3. Cross-correlation functions of sea level at (*a*) Nauru, (*b*) Jarvis, and (*c*) Santa Cruz, with the western Pacific zonal wind index shown in Figure 2. Western Pacific zonal wind leads sea level for positive lags. The vertical axes are in units of standard error of the correlation coefficients.

[*Rasmusson and Wallace*, 1983]. Several significant correlations at other lags are not easily explained.

Direct correlation of sea level records in the central Pacific with the record from Santa Cruz in the Galapagos Island is even more revealing (Figure 4). Here we see several cross-correlation peaks that have significant magnitudes and physically significant time lags. Both cross-correlation functions have a peak near 28 days (Jarvis and Christmas leading Santa Cruz), which is significant at the 98% confidence level. The implied phase speeds are 3.2 and 3.1 m/s, respectively (Table 1). These speeds are in good agreement with the results of *Eriksen et al.* [1983] for the phase speed of a first baroclinic mode Kelvin wave, although about 15% higher than speeds predicted by linear theory.

Another peak, which could be due to the second baroclinic-mode Kelvin wave, is found in both cross-correlation functions near 56 days; again, eastward propagation is implied but at about half the speed of the first peak. The significance of this peak is 95% and 97%. Whereas the first mode peak is a stable feature of the sea level cross correlations, this second mode peak has been found only in the records of the 1982–83 event. Figure 5 shows the cross-correlation function of high-passed sea level at Jarvis and Santa Cruz during non-El Niño conditions. The first mode peak is still highly significant, but now there is no evidence of a second mode Kelvin wave. *Busalacchi and Cane* [1984] forced a linear model of the Pacific with an estimate of the actual winds during the 1982–83 El Niño, finding that the second baroclinic mode was of comparable amplitude to the first mode during the event. We will return to this point shortly.

A third positive correlation peak is found, but with the Galapagos leading the central Pacific stations by about 80 days (Table 1). The propagation speed of 1 m/s to the west appears to be the result of first baroclinic mode, first meridional mode, long Rossby waves that travel at one third the speed of the first-mode Kelvin wave. As with the second-mode Kelvin wave peak, this peak is not usually seen in sea level correlations (Figure 5).

The significant negative correlation, with the central Pacific leading the eastern Pacific by about 10 days (Table 1), is perplexing at first glance. However, the strong first baroclinic mode Kelvin wave signal appears to be in large part contained in eventlike pulses similar to the pulse observed by *Knox and Halpern* [1982]. The highly significant positive skew of the daily mean sea level records (both regular and high-passed) is evidence of the tendency for these pulses to be of positive

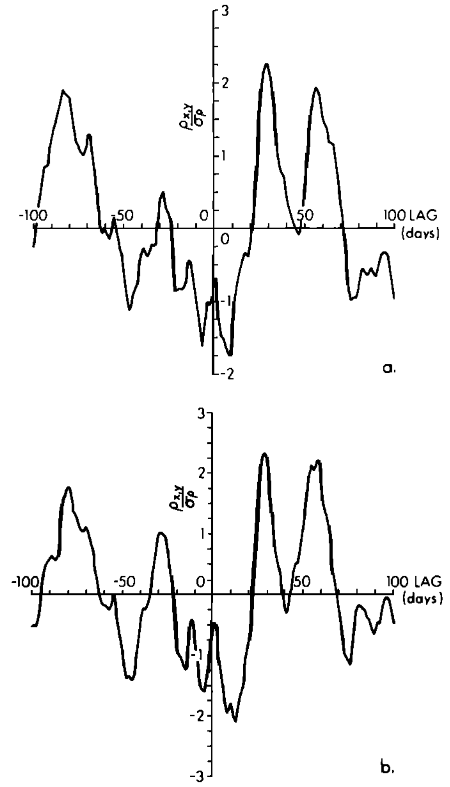

Fig. 4. Cross-correlation functions between sea level in the central equatorial Pacific ((*a*) Jarvis and (*b*) Christmas) and the eastern equatorial Pacific (Santa Cruz) for a time period including the onset of the 1982–83 El Niño. The central Pacific sea level leads for positive lags. Vertical axes are in units of standard error of the correlation coefficients.

elevation. Such sea level events have a typical duration of 15–30 days. When the leading edge of the pulse has reached the Galapagos, the trailing edge has already passed through the central Pacific. Thus there is a small lag between the rise in the east and the fall of sea level in the central Pacific.

The significance levels of these peaks and the observed lags provide strong evidence of the importance of nondispersive equatorial waves prior to and during the onset of the 1982–83 El Niño. Details of the El Niño onset, however, are much different in the central (Jarvis Island) and eastern (Isabela Island) subsurface pressure records. At Jarvis, sea level rose rapidly (about 20 cm in three weeks, beginning near July 1, 1982). A similar sea level rise commenced about 1 month later at the Galapagos Islands (a propagation speed of about 3 m/s) but took nearly six weeks to achieve equal amplitude.

A possible explanation for this difference in rise times is modal dispersion associated with the different phase speeds for each vertical mode. A definitive simulation of this effect requires specification of wind forcing and a numerical model for the ocean's response [e.g., *Busalacchi and Cane*, 1984]. A qualitative test can be obtained as follows: Assume that the sea level response is initially confined to the first two baroclinic Kelvin wave modes K_1 and K_2. Further, assume that the wind forcing is near (but to the west of) Jarvis Island so that both modes (with unknown amplitudes) are in phase at this location. Thus the time history of the sum of the two modes is identical with the observed Jarvis sea level record, so

$$J(t) = A_1K_1(t) + A_2K_2(t) \tag{1}$$

with

$$A_1 + A_2 = 1$$

This signal is then propagated eastward to estimate sea level at the Galapagos Islands,

$$G(t) = A_1K_1(t - \tau_1) + A_2K_2(t - \tau_2) \tag{2}$$

Here, $\tau_i = L/c_i$, where L is the separation between the two islands (approximately 8000 km), and c_i is the free linear phase speed of the ith vertical mode. The amplitudes A_1 and A_2 are adjusted to minimize (in a least squares sense) the deviation of observed and computed sea level.

Observed Galapagos sea level, the first mode contribution, and the sum of modes 1 and 2 are shown in Figure 6 for the best-fit parameters ($A_1 = 0.4$, $A_2 = 0.6$) of (1). Clearly, the agreement of observed and predicted sea level is good (correlation coefficient, $r = 0.93$). The slower Galapagos rise time at the onset of the ENSO event is reproduced well by the calculation. The essentially equal amplitudes of mode 1 and mode 2 agree with theoretical computations of the oceanic response to a sudden change in winds [*Eriksen et al.*, 1983] and model simulations of the 1982–83 event [*Busalacchi and Cane*, 1983]. The most significant deviation between computed and observed Galapagos sea level in Figure 6 occurs in May-June 1982 when this simple model underestimates the observations by about 10 cm. Performing the least squares fit of modal amplitudes for only the period prior to the El Niño onset does not improve the simulation during this period.

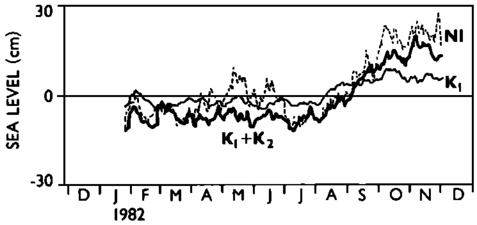

Fig. 6. Isabela Island sea level, model first mode Kelvin wave, and the sum of model first and second mode Kelvin wave contributions at the Galapagos. The model assumptions and calculation are described in the text.

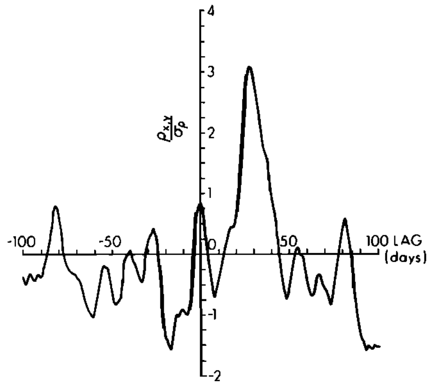

Fig. 5. Cross-correlation between sea level at Jarvis Island and Santa Cruz during non-El Niño conditions. Jarvis leads for positive lags, and the vertical axes are in units of standard error of the correlation coefficients.

6. CONCLUSIONS

We have shown the importance of remote wind forcing in the western Pacific during the onset phase of the 1982–83 El Niño. First and second baroclinic mode Kelvin waves were detected in sea level time series, consistent with the dynamics proposed by *Wyrtki* [1975*a*] for the onset of El Niño conditions. We demonstrate that the different speed at which these two Kelvin wave modes propagate eastward might be responsible for the different shape of the sea level signal in the eastern and central Pacific during the onset. Additionally, we find marginally significant evidence for the existence of first baroclinic mode, long Rossby waves during the early phase of the event.

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REFERENCES

Busalacchi, A. J., and M. A. Cane, Hindcast of sea level variations during the 1982/83 El Nino, *J. Phys. Oceanogr.*, in press, 1983.

Chelton, D. B., Statistical reliability and the seasonal cycle: Comments on "Bottom pressure measurements across the Antarctic Circumpolar Current and their relation to the wind," *Deep-Sea Res.*, *29*, 1381–1388, 1982.

Davis, R., Techniques for statistical analysis and prediction of geophysical fluid systems, *Geophys. Astrophys. Fluid Dyn.*, *8*, 245–277, 1977.

Eriksen, C. C., M. B. Blumenthal, S. P. Hayes, and P. Ripa, Wind-generated equatorial Kelvin waves observed across the Pacific Ocean, *J. Phys. Oceanogr.*, *13*, 1622–1640, 1983.

Firing, E., R. Lukas, J. Sadler, and K. Wyrtki, Equatorial Undercurrent disappears during the 1982-83 El Nino, *Science*, *222*, 1121–1123, 1983.

Gill, A. E., and E. Rasmusson, The 1982–83 climate anomaly in the equatorial Pacific, *Nature*, *306*, 229–234, 1983.

Halpern, D., S. P. Hayes, A. Leetma, D. V. Hansen, and S. G. H. Philander, Oceanographic observations of the 1982 warming of the tropical eastern Pacific, *Science*, *221*, 1173–1175, 1983.

Harrison, D. E., and P. S. Schopf, Kelvin wave-induced anomalous advection and the onset of surface warming in El Niño events, *Mon. Weather Rev.*, *112*, 923–933, 1984.

Knox, R. A., and D. Halpern, Long range Kelvin wave propagation of transport variations in Pacific Ocean equatorial currents, *J. Mar. Res.*, *40*(suppl.), 329–339, 1982.

Luther, D. S., D. E. Harrison, and R. A. Knox, Zonal winds in the central equatorial Pacific and El Nino, *Science*, *222*, 327–330, 1983.

Moore, D. W., and S. G. H. Philander, Modeling of the tropical oceanic circulation, in *The Sea*, vol. 6, edited by E. D. Goldberg, pp. 319–361, John Wiley, New York, 1977.

Rasmusson, E. M., and J. M. Wallace, Meteorological aspects of the El Nino/Southern Oscillation, *Science*, *222*, 1195–1202, 1983.

Roberts, J., and T. D. Roberts, Use of the Butterworth low-pass filter for oceanographic data, *J. Geophys. Res.*, *83*, 5510–5514, 1978.

Sadler, J. C., and B. Kilonsky, Meteorological events during evolution of positive SST anomalies in the equatorial Pacific in 1982, *Trop. Ocean-Atmos. Newslett.*, 16, 1983.

Sciremammano, F., A suggestion for the presentation of correlations and their significance levels, *J. Phys. Oceanogr.*, *9*, 1273–1276, 1979.

Wyrtki, K., El Nino—The dynamic response of the equatorial Pacific Ocean to atmospheric forcing, *J. Phys. Oceanogr.*, *5*, 572–584, 1975*a*.

Wyrtki, K., Fluctuations of the dynamic topography in the Pacific Ocean, *J. Phys. Oceanogr.*, *5*, 450–459, 1975*b*.

Wyrtki, K., Sea level during the 1972 El Nino, *J. Phys. Oceanogr.*, *7*, 779–787, 1977.

Wyrtki, K., The slope of sea level along the equator during the 1982/83 El Nino, *J. Geophys. Res.*, in press, 1984.

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