14. G. L. Gaines, Jr., *Insoluble Monolayers at Liquid-Gas Interfaces*, I. Prigogine, Ed. (Wiley, New York, 1966).
15. D. R. Day and H. Ringsdorf, *Makromol. Chem.* **180**, 1059 (1979).
16. H. O. Ribi, unpublished results.
17. D. Day and J. B. Lando, *Macromolecules* **13**, 1478 (1980); *ibid.*, p. 1483.
18. R. Sonnenfeld and P. K. Hansma, *Science* **232**, 211 (1986).
19. Diamond dust: 40 to 60 μm wide, Aesar 070286; glue: tiny amounts of Epoxi-Patch from Hysol Division, the Dexter Corporation.
20. Arlunya TF5000 Image Processor, Princeton Electronic Products.
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GEOSAT Altimeter Observations of Kelvin Waves and the 1986–87 El Niño

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Two years of GEOSAT altimeter observations are used to investigate the response of sea level to anomalous westerly wind bursts in the tropical Pacific Ocean before and during the 1986–87 El Niño. Sea level time series along the equator show examples of both positive and negative anomalies of 10-centimeter amplitude and 2- to 4-week time scale propagating across the Pacific with phase speeds of 2.4 to 2.8 meters per second, suggesting downwelling and upwelling Kelvin waves, respectively. A comparison of island wind observations with sea level indicates one instance (May 1986) in which a positive sea level anomaly can be related to westerly winds caused by a cross-equatorial cyclone pair in the western Pacific. This episode was followed by additional wind bursts later in the year, and finally by sustained westerlies in the western Pacific during November–December 1986, at the height of El Niño. The GEOSAT observations reveal the sea level response to these meteorological events and provide a synoptic description of the El Niño oceanographic phenomenon.

IT HAS BEEN SUGGESTED THAT THE onset of sea surface warming in the eastern tropical Pacific during an El Niño/Southern Oscillation (ENSO) event may be triggered by short, intense bursts of westerly winds in the western Pacific (*1, 2*). According to this scenario, anomalous westerlies generate downwelling Kelvin waves in the ocean, which then propagate eastward along the equator. Since these waves produce eastward zonal current anomalies and since the mean zonal sea surface temperature gradient is negative (colder eastward), surface temperatures in the eastern Pacific increase as a result of the advection of warm water zonally along the equator (*3, 4*).

Although other mechanisms may influence the development of an ENSO event, there are several reasons for believing that westerly wind bursts play a crucial role in the initial stages. Westerly bursts are known to occur more frequently in the western Pacific just before an ENSO event (*1*), often in association with the formation of cross-equatorial cyclone pairs (*2*). The sea level response to these bursts appears in tide gage records from island stations, primarily in the far western Pacific (*5*). Also, moored current meter records show that the passage of a Kelvin wave front generates eastward zonal transport in the surface mixed layer (*6*). Because of the vast size of the Pacific and the almost complete absence of islands in the eastern half, it has been difficult to document the oceanic response to these wind anomalies.

We examine 2 years of sea level time series along the equator in the Pacific based on observations obtained from the U.S. Navy altimeter satellite GEOSAT (*7, 8*). We first focus on one unusually strong westerly wind burst (May 1986), which forced a disturbance in sea level that propagated across the Pacific. This wind–sea level event is noteworthy because it led to several predictions of El Niño (*9–11*). We then examine how sea level behaved along the equator during the El Niño, which occurred later that year.

GEOSAT (GEOdetic SATellite), launched in March 1985, circles the earth 14 times per day and yields coverage between +72° and −72° latitude. Its radar altimeter provides a continuous record of sea level along the satellite ground track with a precision of approximately 3 cm. Previous work based on the limited sets of altimeter data collected in the 1970s (*12*) demonstrated

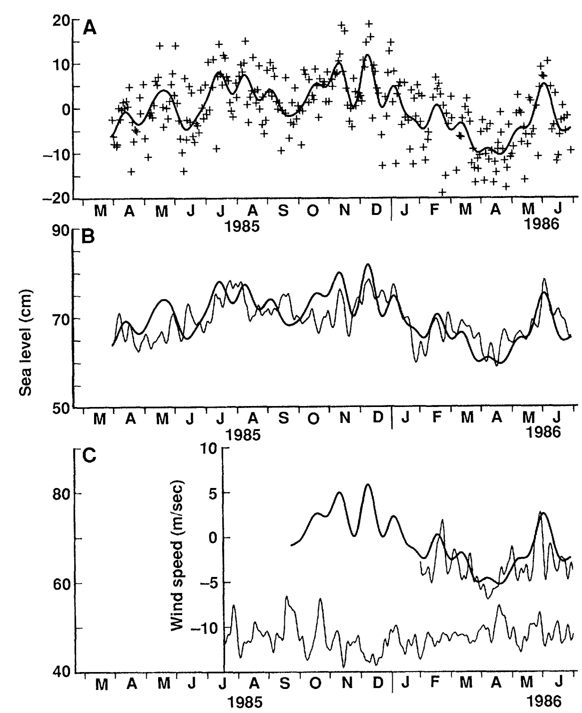

Fig. 1. (**A**) Sea level time series derived from 15 months of GEOSAT altimeter data near Christmas Island (2°N, 158°W). Crosses represent individual altimeter observations as determined by least-squares adjustment of crossover differences. The smooth curve shows an objective analysis fit to the same measurements, based on a decorrelation time scale of 15 days and a noise level of 5 cm. (**B**) Comparison of altimeter-derived sea level from (A) with low-pass filtered tide gage time series for Christmas Island. (**C**) Comparison of altimeter-derived sea level from (A) (heavy curve) with low-pass filtered east-west wind component for Nauru Island (upper light curve) and Christmas Island (lower light curve). The Nauru wind data have been offset in time by 23 days; the Christmas wind data have been offset in speed by 5 m/sec.

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that temporal change of sea level could be accurately determined from altimetric measurements at "crossover points" (intersections of ascending and descending satellite ground tracks). In the following analyses we use the difference in sea level between the two times of each crossover point (the crossover difference) to construct time series of sea level. This method has been described by Miller *et al.* (*13*) and Fu and Chelton (*14*).

Figure 1A shows an example of a sea level time series computed for a 2° by 8° (latitude by longitude) area centered on 2°N, 158°W, the location of Christmas Island, where tide gage data are available. The altimetric record spans the 15-month period from 1 April 1985 to 30 June 1986. During this time 300 altimeter profiles were obtained in the sample area yielding approximately 4000 crossovers. The elongated 2° by 8° area provides sampling with high temporal resolution (one pass every 1.5 days) while still resolving the zonally banded structure of the equatorial region. Plotted in Fig. 1A are the 300 individual heights determined from the crossover differences by least-squares analysis, together with an objective analysis fit to these data. The root-mean-square scatter of the observations about the fitted line is approximately 4 cm. Much of this residual variability may be due to real sea level signals at time scales shorter than 15 days (the decorrelation time chosen for the objective analysis) or incomplete correction of environmental errors, or both (*15*).

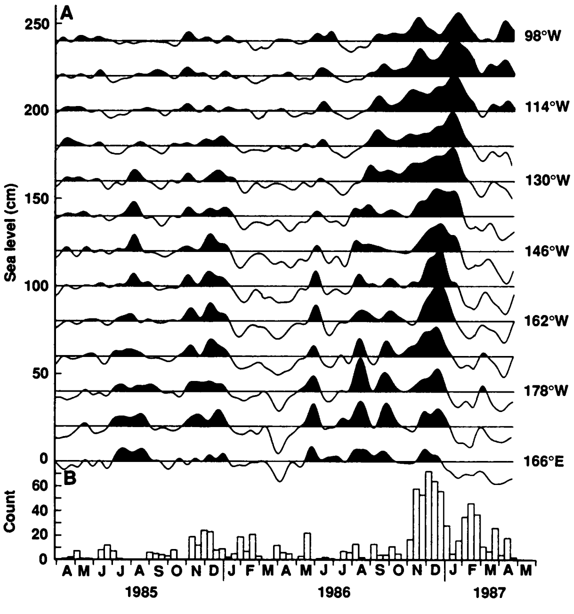

Fig. 2. (**A**) Altimeter-derived sea level time series at 13 locations (8° intervals between 166°E and 98°W) along the equator, April 1985 through April 1987. Sea level was computed in the same manner as in Fig. 1A. Horizontal lines indicate zero mean values for the first 12 months (April 1985 through April 1986) with 20-cm offset between pairs of series. (**B**) Histogram along the *x*-axis indicating the time intervals during which westerly wind bursts were persistently observed in the far western equatorial Pacific. The histogram was constructed by summing the number of days for which analyzed westerly winds greater than 5 knots were found in each 5° by 5° box in the region 0° to 5°S, 130°E to 170°E (*19*).

Figure 1B shows a comparison of the altimeter time series with low-pass filtered tide gage data from Christmas Island. Although there are occasions when the two records disagree by as much as 5 to 10 cm, the root-mean-square difference is only 3 cm. Considering the different spatial and temporal sampling characteristics of the altimeter and tide gage, the agreement is remarkable. The occasional discrepancies may reflect real differences between measurements of sea level made in the open ocean versus those made at an island. We conclude that GEOSAT altimeter data are adequate for monitoring sea level variations in the tropics with an accuracy of a few centimeters.

Both the altimeter and the tide gage records in Fig. 1B display energetic 10- to 50-day fluctuations, time scales at which wind-driven Kelvin waves have been found in the central Pacific (*5*). To investigate whether the observed features are related to either local or remote wind forcing, a comparison is made in Fig. 1C between the altimeter sea level near Christmas Island and the zonal wind component measured at Christmas Island and Nauru Island (0.5°S, 167°E), 3850 km west of Christmas Island. (In this figure, the Nauru Island time series has been offset by 23 days, the lag time of maximum cross correlation between Nauru zonal winds and sea level near Christmas Island.) Figure 1C shows that a correlation exists between Nauru zonal winds and sea level near Christmas, but not between Christmas zonal winds and sea level measured nearby. Two sharp peaks in sea level, on 23 February and 4 June 1986, coincide with westerly wind bursts 23 days earlier (31 January and 12 May 1986) at Nauru. (A lag time of 23 days corresponds to a phase speed of 1.9 m/sec, which is somewhat smaller than the theoretical speed, 2.2 to 3.0 m/sec, of a first vertical mode Kelvin wave.)

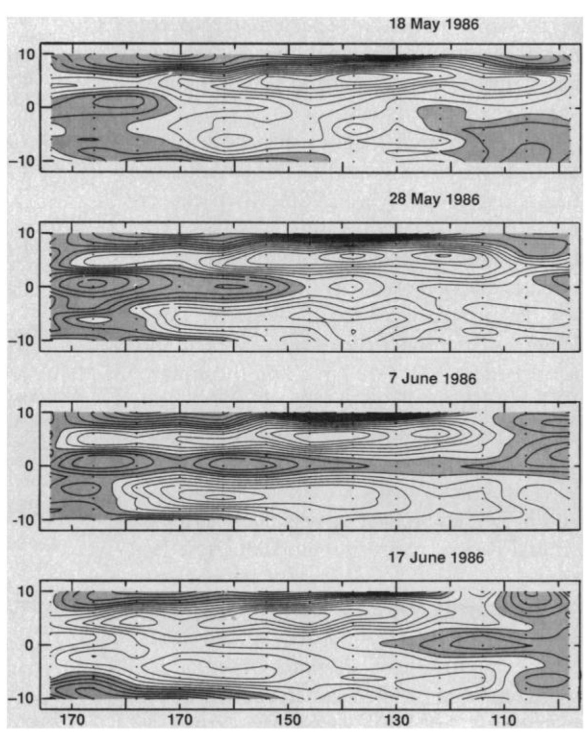

Fig. 3. Altimeter-derived maps of sea level constructed at 10-day intervals after the onset of the May 1986 wind burst event. Sea level was computed on a 2° by 8° grid (dots) in the same manner as in Fig. 1A. Contours are at 2-cm intervals and represent sea level anomalies relative to an annual mean (April 1985–86). Positive values are shaded. Eastward propagation along the equator is clearly evident and is interpreted as a downwelling Kelvin wave forced by anomalous westerly winds.

Although the two wind bursts display similar amplitudes (2 to 3 m/sec) at Nauru, other evidence suggests that the May burst was actually part of a larger, more intense atmospheric disturbance. A satellite image of cloud cover over the western Pacific on 18 May 1986 reveals a pair of tropical cyclones arranged symmetrically between 10°N and 10°S of the equator along 160°E (*16*). The two cyclones, Lola and Namu, first appeared on 14 May 1986 at approximately these positions, then rapidly diverged northward and southward.

The effect of this massive westerly burst on equatorial sea level can be seen in a sequence of 13 altimeter time series (Fig. 2A) computed at 8° longitude intervals and spanning the 10,500-km distance between 166°E and 98°W along the equator. Beginning in mid-May 1986, sea level rose rapidly over the western and central Pacific, reaching a maximum positive anomaly of 13 cm at 174°E on 31 May. This disturbance subsequently propagated eastward with generally decreasing amplitude. Estimates of phase speed determined by linear regressions of the arrival time of maximum sea level as a function of longitude indicate two distinct longitudinal regimes. In the western and central Pacific (166°E to 146°W) the phase speed was 9.3 m/sec; however, in the east (146°W to 114°W) it was 2.8 m/sec. The former value is much greater than the speeds predicted for free Kelvin waves in the Pacific (2.2 to 3.0 m/sec) (*5, 17*). The latter value, however, is only 7% higher than expected in the region 146°W to 114°W. The large apparent zonal variation in phase speed could be due to differences in local versus remote forcing effects along the equator. The formation of a cross-equatorial cyclone pair is generally preceded by the appearance of zonally oriented, low-pressure troughs near the equator in each hemisphere (*2*). These cause anomalous westerlies to occur over a broad longitudinal band (for example, 30° to 40°), often extending east of the international dateline. Thus, sea level in the western and central Pacific may be responding to both local and remote forcing, while the eastern Pacific may be responding to only remote forcing, in the form of a free Kelvin wave. More information about the spatial structure of the wind field is obviously needed to properly interpret the altimeter time series.

We have focused on the May 1986 event because it was thought to mark the onset of an El Niño; however, the altimetric records in Fig. 2A reveal that at least 5 months separated the May event and the mature stages of El Niño (*18*). During the intervening half-year, sea level behaved very differently as a function of longitude. In the western Pacific (166°E to 170°W), Fig. 2A shows 10- to 15-cm positive pulses in August, September–October, and November–December followed by generally negative anomalies beginning in January 1987. In the central Pacific (162°W to 138°W), the pulses were smaller in amplitude, and sea level remained fairly constant except for a large (24-cm), long (3-month) pulse in November–January. In contrast to both the western and central Pacific, sea level in the eastern Pacific (130°W to 98°W) showed the pulses superimposed on a steady, 25-cm rise between July and January; sea level then dropped abruptly in January–February 1987.

In order to determine if this pattern of sea level change could also be associated with westerly bursts, we examined wind summaries in NOAA's monthly *Climate Diagnostics Bulletin* (*19*). Indicated in Fig. 2B are periods when westerly bursts were persistently observed in the far western tropical Pacific (0° to 5°S, 130°E to 170°E). The histogram was constructed by summing the number of bursts reported in consecutive 10-day intervals. The most striking aspect of this plot is the correspondence between episodes of well-developed westerlies and positive sea level anomalies (Fig. 2A) during the El Niño time interval, November 1986 through March 1987. Strong westerlies in November–December produced a maximum sea level anomaly in the central Pacific, which then propagated eastward at a phase speed of about 2.4 m/sec (measured between 170°W and 98°W). The westerlies diminished in January 1987, at which time sea level anomalies declined and eventually turned negative over the western Pacific. (This negative sea level anomaly also propagated eastward, suggesting an upwelling Kelvin wave.) Subsequently, westerlies resumed in February 1987, producing another smaller, positive sea level pulse which propagated eastward with a speed of about 2.8 m/sec (measured between 170°W and 98°W). In addition to these two large episodes and the May 1986 event, Fig. 2 shows a number of other occasions when westerly bursts were followed by pulses of rising sea level. However, eastward propagation is not always apparent. (The most notable example of this inconsistency occurred in November–December 1985, when positive sea level anomalies appeared almost simultaneously across the entire Pacific.)

Figure 3 shows a series of four sea level anomaly maps generated at 10-day intervals beginning on 18 May 1986, when the cyclone pair, Lola and Namu, was closest to the equator. These maps demonstrate the remarkably narrow meridional scale of the sea level response to a westerly burst. Whereas the zonal scale of the sea level pulse is the order of 10,000 km along the equator (7 June 1986), the meridional scale is only 200 km (e-folding distance at 130°W) (*20*). Off the equator, the maps show negative sea level anomalies oriented zonally along 5°N and 5°S. These reflect divergences caused by annual variations in the winds at these latitudes.

In summary, by taking advantage of the unprecedented temporal and spatial coverage of the GEOSAT altimeter observations, we have been able to construct a synoptic picture of sea level variability across the entire tropical Pacific. Sea level time series generated at regularly spaced intervals across the Pacific reveal a complex, zonally dependent response to westerly wind anomalies before and during the 1986–87 El Niño. Kelvin waves forced by wind bursts, such as the May 1986 event, change in amplitude as they propagate into the eastern half of the Pacific. During the El Niño, sea level variability in the western and central Pacific was dominated by month-long Kelvin wave pulses, while in the eastern Pacific these pulses were superimposed on a gradual 25-cm increase in sea level over 6 months. These observations should provide new insight into the mechanisms responsible for the initiation and development of El Niño.

REFERENCES AND NOTES

1. D. S. Luther, D. E. Harrison, R. A. Knox, *Science* **222**, 327 (1983).
2. R. A. Keen, *Mon. Weather Rev.* **110**, 1405 (1982).
3. S. G. H. Philander, *J. Phys. Oceanogr.* **11**, 176 (1981).
4. D. E. Harrison and P. S. Schopf, *Mon. Weather Rev.* **112**, 923 (1984).
5. C. C. Eriksen, M. B. Blumenthal, S. P. Hayes, P. Ripa, *J. Phys. Oceanogr.* **13**, 1622 (1983).
6. R. A. Knox and D. Halpern, *J. Mar. Res.* **40** (suppl.), 329 (1982).
7. R. Cheney *et al.*, *Eos* **67**, 1354 (1986).
8. *Johns Hopkins APL Tech. Digest* **2** (1987).
9. M. A. Cane, S. E. Zebiak, S. C. Dolan, *Nature (London)* **321**, 827 (1986).
10. R. A. Kerr, *Science* **232**, 155 (1986).
11. ———, *ibid.*, p. 1604.
12. R. E. Cheney and J. G. Marsh, *Eos* **62**, 743 (1981).
13. L. Miller, R. Cheney, D. Milbert, *Geophys. Res. Lett.* **13**, 475 (1986).
14. L-L. Fu and D. B. Chelton, *J. Geophys. Res.* **90**, 4721 (1985).
15. The following environmental corrections were applied to the GEOSAT altimeter data: earth and ocean tides, refraction due to wet and dry troposphere, and ionosphere. For details, see R. E. Cheney *et al.*, *GEOSAT Altimeter Geophysical Data Record (GDR) User Handbook* [*NOAA (Natl. Oceanic Atmos. Adm.) Tech. Mem. NOS NGS-46* (July 1987)].
16. R. M. DeAngelis, Ed., *Mariners Weather Log* **4**, 224 (1986).
17. R. Lukas, S. P. Hayes, K. Wyrtki, *J. Geophys. Res.* **89**, 10425 (1984).
18. R. A. Kerr, *Science* **235**, 744 (1987).
19. V. E. Kousky and J. D. Kopman, Eds., *Climate Diagnostics Bulletin* (National Weather Service, National Oceanic and Atmospheric Administration, Washington, DC, 1987), vol. 4.
20. This is smaller than the predicted e-folding distance of 500 km for a first baroclinic mode Kelvin wave with a phase speed of 2.8 m/sec. However, it is consistent with in situ temperature measurements (M. McPhaden, personal communication).

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