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The Slope of Sea Level Along the Equator During The 1982/1983 El Niño

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Observed deviations of monthly mean sea level at seven island stations along the equator in the Pacific have been superimposed on the mean dynamic topography to determine the variations of the east-west slope of sea surface topography during the 1982/1983 El Niño. The normal east-west slope is eliminated in January 1983 when the bulk of warm water flowing eastward has reached the coast of South America. The sea surface remains essentially flat from January to June 1983, although zonal winds are very weak until April only. The slope requires several months to be reestablished, and in October and November, sea level along the entire equator is 10 cm or more below normal, indicating a net loss of warm water from the equatorial Pacific.

1. INTRODUCTION

The unexpected El Niño event of 1982/1983 started in July 1982, opposite the season when most earlier events began. It also became the strongest event recorded in the last century [*Cane*, 1983; *Rasmussen and Wallace*, 1983].

The response of the ocean to the collapse of the southeast trade winds [*Wyrtki*, 1975*a*] consists of a draining of warm surface water from the western Pacific, an eastward flow of water in the central Pacific, an accumulation of warm water in the eastern Pacific, and a corresponding response of the thermocline and of sea level. This response has been documented for the El Niño events of 1972/1973 and 1976 [*Wyrtki*, 1977, 1979]. The dynamics of this process have been modeled by *McCreary* [1976] and by *O'Brien et al.* [1980]. Most of these studies rely on charting sea level in relation to the long-term mean or on modeling events in relation to the mean state of the ocean and do not take into account the existing mean structure. A notable exception is the work by *Busalacchi and O'Brien* [1980], which includes the mean east-west slope of the thermocline.

In this study I wish to relate the observed response of sea level along the equator during the 1982/1983 El Niño event to the mean dynamic topography along the equator so that the actual topography of the sea surface can be determined. It will then be possible to discuss the actual topography of sea level along the equator in relation to the atmospheric forcing.

2. THE MEAN SLOPE OF SEA LEVEL ALONG THE EQUATOR

The existence of a rise of dynamic topography along the equator from the eastern to the western Pacific Ocean has been known since the work of *Montgomery and Palmen* [1940], and an observed profile of dynamic height anomaly has been published by *Lemasson and Piton* [1968]. Information about the variability of this slope has only been accumulated in recent years. A profile of dynamic height relative to 500 dbar along the equator from the coast of Ecuador to the Indonesian Island of Halmahera is shown in Figure 1. The profile is based on all hydrographic stations between 1°N and 1°S and uses the same data set as the maps of dynamic height drawn by *Wyrtki* [1975*b*]. The dynamic topography of 500 relative to 1000 dbar is virtually flat along the equator [*Wyrtki*, 1975*b*], and consequently, the sea surface is adequately represented by the topography relative to 500 dbar. The total variability of dynamic height during the Shuttle Experiment [*Wyrtki et al.*, 1981] at 150°, 153°, and 158°W is also shown by vertical bars. The mean profile is based on a spline fit to the data.

Sea level observations at several stations close to the equator have been used to illustrate its variability in relation to the mean profile of dynamic height. Vertical bars show the standard deviations of monthly mean sea level at each station as well as the maximum positive and negative deviation of monthly means relative to the long-term mean at each station prior to 1982. Sea level records are longer than 20 years at Kanton, Christmas, and the Galapagos Islands but are only 7 years at Tarawa, Nauru, and Fanning and three years at Kapingamarangi, which may result in some bias of the extremes. This diagram indicates that the slope between Christmas and the Galapagos Islands could occasionally be nil, but this did not happen during the period of common record. On the other hand, sea level at Nauru and Tarawa has always been higher than sea level at the Galapagos during the last 7 years, which include the 1976 El Niño event.

For comparison the zonal wind stress along the equator averaged from 4°N to 4°S and, based on the data from *Wyrtki and Meyers* [1976] is also shown in Figure 1 for June, December, and the annual mean. It is apparent that the region of maximum slope is east of that of maximum stress. The depth of the upper layer should play a role in explaining this discrepancy. The mean depth of the 14°C isotherm according to *Meyers* [1979] is shown for comparison. The same wind stress should result in a stronger slope where the upper layer is shallower. An analysis of the variability of the slope of isotherms along the equator has been given by *Halpern* [1980, 1984].

3. THE WINDS ALONG THE EQUATOR IN 1982/1983

Monthly mean wind vectors for each 5-degree square along the equator have been obtained from the Climate Analysis Center in Washington, D. C., through the courtesy of E. Rasmusson. These data are based on the daily analysis of winds at 850 mbar and are not necessarily winds near the sea surface. The relationship between surface winds and winds of 850 mbar has been discussed by *Sadler and Kilonsky* [1981] and *Halpern* [1979]. The number of direct observations from ships is, unfortunately, insufficient over large parts of the tropical Pacific to draw reliable monthly mean wind maps. The values at 2.5°N and 2.5°S have been averaged to draw the profiles of monthly mean zonal wind speed along the equator; these profiles are shown in Figure 2.

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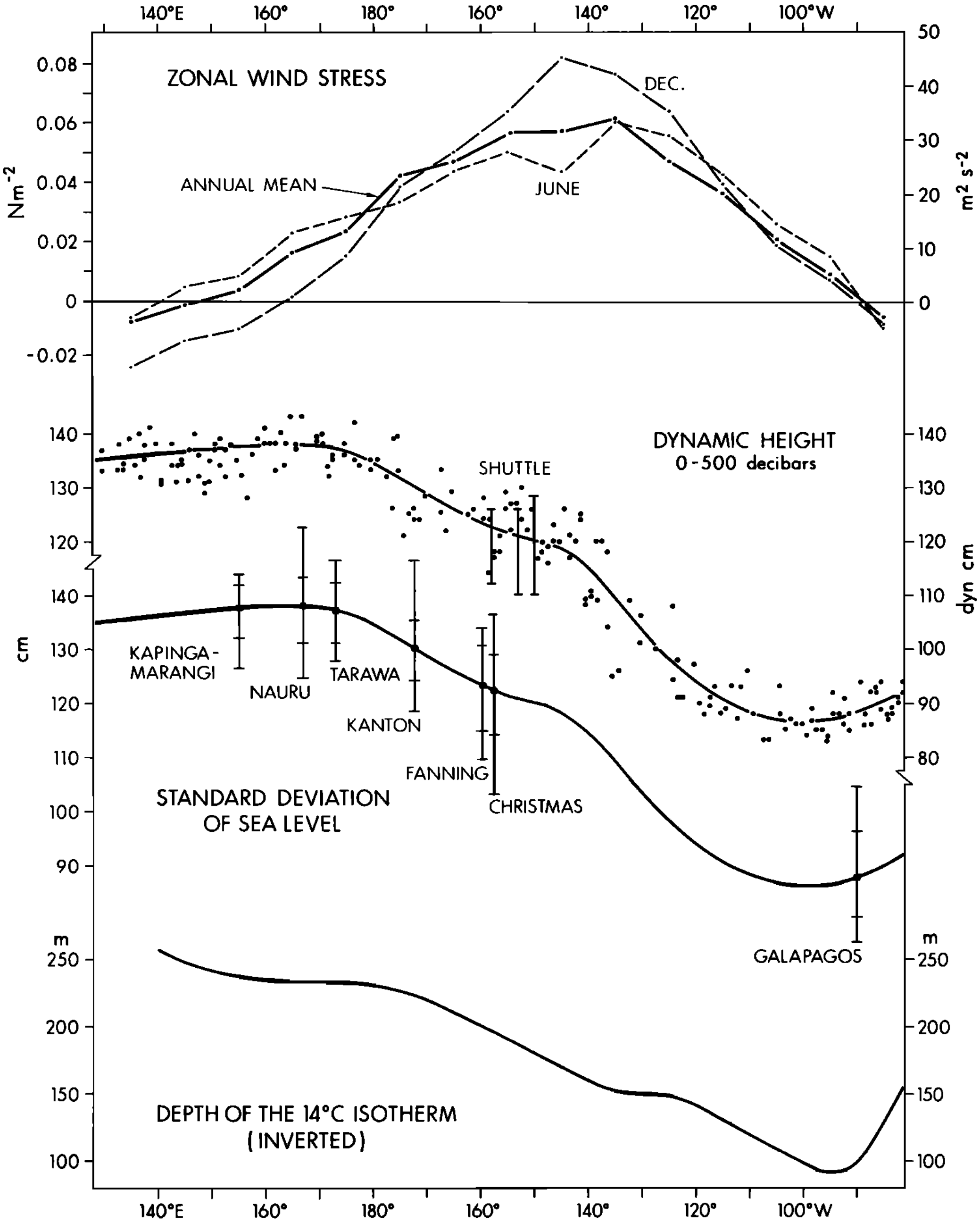

Fig. 1. Relations between wind, dynamic height, sea level, and thermocline depth along the equator in the Pacific: (top) zonal wind stress (westward positive) for June, December, and the annual mean; (upper middle) dynamic height relative to 500 dbar within 1° of latitude from the equator—variations during the Shuttle Experiment (43 stations at three longitudes each) are shown by bars; (lower middle) variability of sea level in relation to the mean dynamic topography giving the highest and lowest monthly mean and the standard deviation of monthly means at sea level stations near the equator; (bottom) depth of the 14°C isotherm according to *Meyers* [1979].

In June of 1982 the southeast trade winds along the equator were still essentially normal, but north of New Guinea, anomalous westerly winds had already appeared. In July, westerly winds covered the entire equatorial region between Indonesia and the date line, a situation that was highly abnormal. This field of westerly winds intensified and propagated eastward as far at 150°W in November. During the same period, the area of southeast trades over the eastern Pacific shrank steadily. In December 1982, east winds appear temporarily over the western Pacific; they are related to a large and strong anticyclonic circulation cell centered southeast of Japan.

From January to March 1983 the southeast trade winds decreased further over the eastern Pacific, and westerly winds remained over the central Pacific. The largest wind anomaly had shifted to the southern hemisphere, and northerly wind prevailed over the equator. By March, mean zonal winds were less than 3 m s^{-1} along the entire equator. Since the wind stress is proportional to the square of the wind speed, and since winds were weak and variable at that time, there was virtually no appreciable zonal wind stress present during March 1983. During April and May, the southeast trade winds along the equator started to reappear; they became stronger in June, and in July the zonal equatorial winds regained their normal strength.

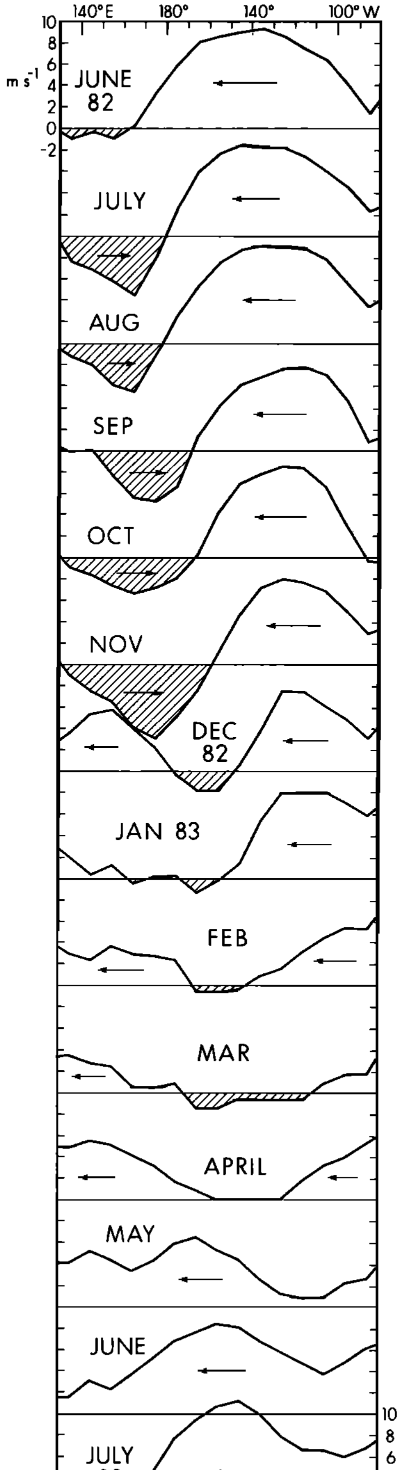

Fig. 2. Zonal wind speed at 850 mbar along the equator between 5°N and 5°S from June 1982 to July 1983 in meters per second (positive westward).

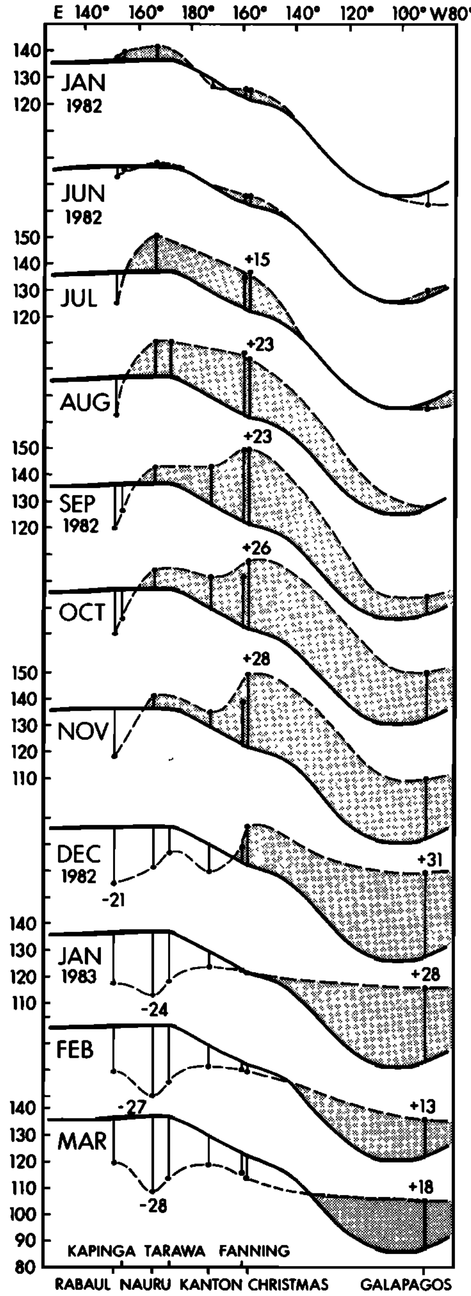

Fig. 3. East-west profiles of the sea surface along the equator in the Pacific. Monthly mean derivations of sea level from the long-term mean are superimposed on the mean dynamic topography of the sea surface relative to 500 dbar in dynamic centimeters. Maximum sea level deviations are indicated in centimeters.

4. The Sea Level Slope in 1982/1983

Sea level observations at eight stations near the equator have been used to construct the mean monthly east-west profile of sea level along the equator during the 1982/1983 El Niño event. Deviations of monthly mean sea level from the mean sea level of the period 1975 to 1981 at each station were computed and superimposed on the profile of mean sea level derived from hydrographic data in Figure 1. The resulting profiles of sea level for each month are shown in Figures 3 and 4 in relation to the mean profile.

In January and June of 1982, sea level deviated only insignificantly from the mean slope by a few centimeters (Figure 3). Between February and May, sea level in the area between Kapingamarangi and Tarawa was about 8 cm above normal (Figure 5), and a peak of +12 cm was observed at Nauru in March 1982. The peak at Nauru is partially a local effect caused by swell entering the harbor from the west. This weak but significant increase of sea level above normal in the western Pacific might be interpreted as a buildup prior to El Niño. The observations agree with an analysis by *Meyers and*

Donguy (1983) that was based on XBT sections; they report a relative maximum thermocline depression in March-April 1982 near 160°E. The buildup of sea level in 1982 was much smaller than before previous El Niño events and should not be construed as a cause for the 1982 El Niño. Previous El Niño events were usually preceded by periods of strong southeast trade winds, which led to a considerable depression of the thermocline in the western equatorial Pacific and to a rise of sea level [*Wyrtki*, 1975*a*]. Such anomalously strong southeast trade winds did not precede the El Niño of 1982/1983.

With the appearance of westerly winds over the western Pacific in July 1982, sea level immediately responded. It dropped at Rabaul and rose between Nauru and Christmas, causing a strong deformation of the mean east-west slope. The generated bulge of water advanced eastward as an equatorial Kelvin wave [*McCreary*, 1976] and increased sea level at Christmas to +23 cm in August. The first rise of sea level in the Galapagos Islands, signifying the arrival of the Kelvin wave, occurred in September, but the steepest rise did not occur before early October [*Wyrtki*, 1984*a*]. As the westerly winds propagated eastward from July through November, sea level in the western Pacific decreased, and a peak of +28 cm was reached at Christmas Island in November. The passage of the Kelvin wave near Christmas Island was observed by direct current measurements [*Firing et al.*, 1983], which showed eastward surface flow from mid-September to mid-December. The average eastward flow during these 80 days was 74 cm s^{-1}, with a peak of 140 cm s^{-1}, and represents a particle displacement of 5000 km. By December 1982 the Kelvin wave had passed Christmas Island, and a peak in sea level of +31 cm had been reached at the Galapagos Islands.

In January 1983, sea level in the western Pacific had decreased to 20 cm below normal, had returned to normal at Christmas Island, and was 28 cm above normal at the Galapagos Islands, virtually eliminating the normal east-west slope of sea level. In fact the east-west profile of sea level along the equator is flat (Figure 4). East of 140°W the southeast trade winds are still blowing in January with about normal strength, but they decrease substantially in February and have vanished in March. During this time, sea level at the Galapagos Islands decreases slightly as the Kelvin wave propagates poleward away from the equator along the coast of America and is reflected westward in the form of planetary waves. During February, March, and April, there is essentially no east-west wind stress along the equator, since wind velocities are very small (Figure 2), and when these velocities are squared it leads to even smaller values of wind stress. The disappearance of the east-west slope in January 1983 may have been a momentary result caused by the Kelvin wave arriving at the coast of South America, but the flat topography in April and May was the result of absent winds in the months before.

From May to July 1983 the trade winds along the equator returned; they were about normal in August and stronger than normal in September and October. During this time, the east-west slope of sea level was slowly being restored, but the process took surprisingly long. In May and June, sea level along the equator remained essentially flat, although the winds increased along the equator. In July it dropped in the east and rose at Tarawa and Nauru, restoring a slope of about 25 cm. By August, sea level at the Galapagos Islands had returned to normal, but in the central Pacific it was still 15 cm and in the western Pacific 20 cm below normal. In September and October, when equatorial winds are stronger than normal, sea level dropped at the Galapagos Islands and increased slightly in the western Pacific (Figure 4). The sea level profile of October shows an east-west sea level difference of about 45 cm, nearly normal, but actual sea levels were 10 to 20 cm below normal at all stations. This general drop in sea level seems to be the result of a draining of warm water from the equatorial Pacific during El Niño.

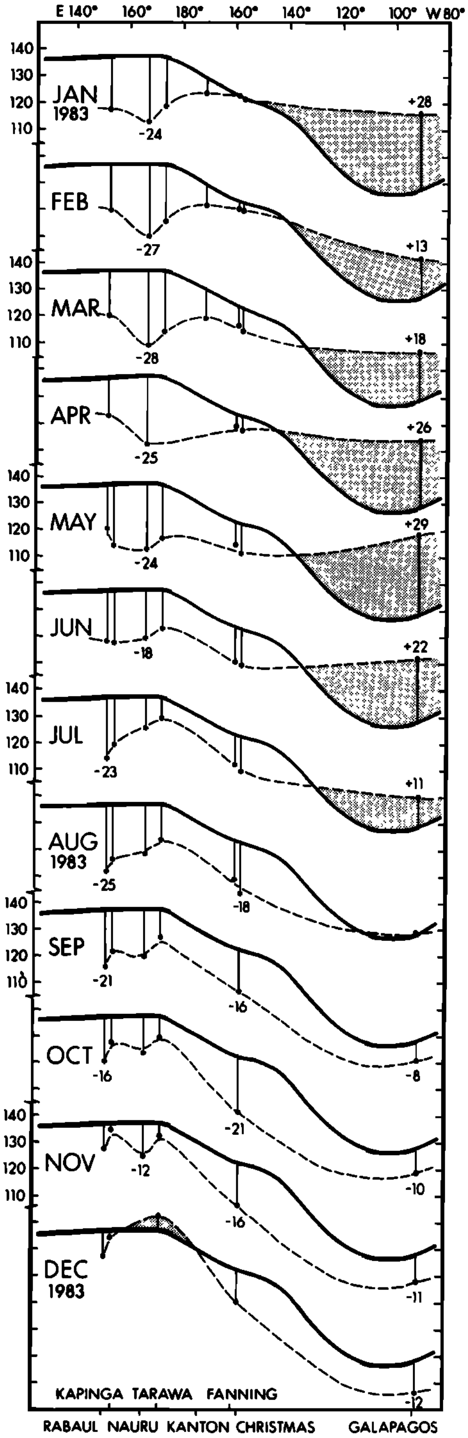

Fig. 4. East-west profiles of the sea surface along the equator in the Pacific. Monthly mean deviations of sea level from the long-term mean are superimposed on the mean dynamic topography of the surface relative to 500 dbar in dynamic centimeters. Maximum sea level deviations are indicated in centimeters.

Discussion and Conclusions

The slope of sea level along the equator is, of course, a

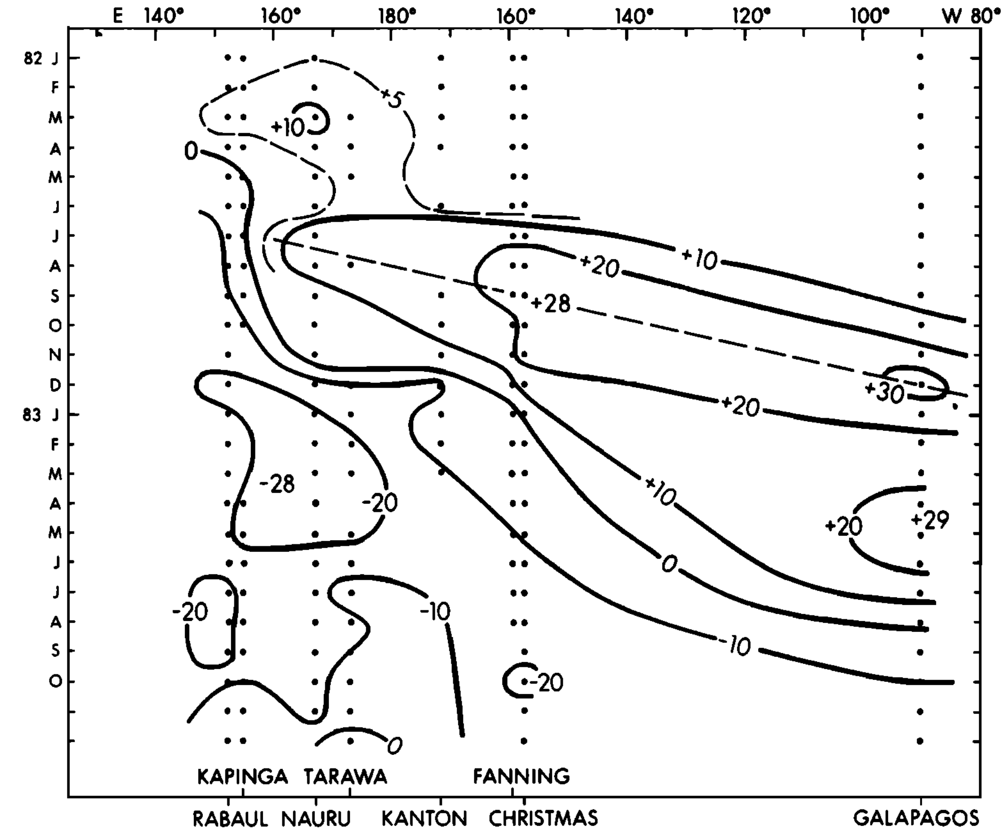

Fig. 5. Deviations of monthly mean sea level, in centimeters, from the long-term mean at stations along the equator during 1982 and 1983.

unique parameter because of the disappearance of the Coriolis acceleration and because it can be affected by the propagation of equatorial Kelvin waves. On the other hand, changes in the east-west slope are not limited to the equator but have considerable structure in the meridional direction as well. This is obvious from maps of sea level anomalies during the 1982/1983 El Niño [*Wyrtki*, 1984*b*]. The draining of water from the western Pacific affects the area from 20°N to 15°S, and the rise of sea level along the eastern side of the ocean propagates to much higher latitudes, but movements of water from west to east are chiefly concentrated in the equatorial waveguide, although the entire equatorial current system is affected and altered. The large-scale response of sea level away from the equator during the 1982/1983 El Niño will be discussed elsewhere.

The first decisive change of the equatorial wind field occurred in July 1982 and triggered an equatorial internal Kelvin wave that traveled eastward. The first rise of sea level of 8 cm at the Galapagos Islands took place between August 24 and September 8, approximately 45 days later. This resulted in a speed of about 3 m s^{-1} for the Kelvin wave, in agreement with theory and with observations made in 1980 by *Knox and Halpern* [1982]. The second, more dramatic rise of 20 cm between September 26 and October 8 can probably be attributed to subsequent wind events in the western Pacific.

In contrast to these fast-traveling Kelvin waves the eastward propagation of the peak in sea level is much slower. A maximum of sea level appears at Nauru and Tarawa in July and August (Figure 5). The maximum reaches the Line Islands in September and does not appear at the Galapagos Islands before December. The peak in sea level advances eastward with a speed of about 1 m s^{-1}, much slower than the speed of first- or second-mode Kelvin waves. Consequently, one must conclude that the observed response is the accumulated effect of many Kelvin waves and reflected planetary waves as caused by a slowly eastward moving field of westerly winds as well as by the purely local response to these winds. Models of the response of sea level to the observed winds seem to simulate the observed response rather correctly [*Busalacchi and Cane*, 1984; *Gill and Rasmussen*, 1983].

During the 1982/1983 El Niño, the east-west slope of sea level along the equator disappeared twice: in January 1983 and in April and May 1983. The disappearance in January was related to the arrival of the sea level peak at the eastern side of the ocean. This occurred while east winds were still blowing over the eastern half of the ocean from the coast to about 130°W. At this time the slope was not in equilibrium with the wind stress, and its disappearance was a remote dynamical effect. In contrast, winds along the equator were extremely weak between February and April. This lack of wind stress was followed by a complete disappearance of the slope in April and May.

The recovery of the east-west slope was a very slow process. While winds had returned to normal in July 1983 and were stronger than normal in September and October, sea level responded very slowly. In the east, sea level returned to normal in August and dropped below normal in September and October, but in the central and western ocean sea level increased only slowly and stayed more than 10 cm below normal until November. In fact in November the entire profile of sea level was 10 cm or more below normal. This seems to indicate a loss of warm water from the equatorial Pacific during El Niño and supports the speculation that El Niño may constitute an energy relaxation of the ocean-atmosphere system in which an excessive accumulation of heat and potential energy in the western equatorial Pacific and over Indonesia is released.

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