The Response of Sea Surface Topography to the 1976 El Niño[1]

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ABSTRACT

The response of sea level in the equatorial Pacific Ocean during the 1976 El Niño event is analyzed and compared with the response during the stronger El Niño event in 1972. Monthly mean maps of sea surface topography illustrate the large horizontal scale of the internal wave associated with El Niño. Strong equatorial trade winds in 1975 increase sea level in the western Pacific. The relaxation of the wind in January 1976 allows an internal wave to form and proceed eastward, raising sea level along the eastern side of the ocean. This is followed by a year-long decline of sea level in the west, by an intensification of the North Equatorial Countercurrent and by a slackening of the South Equatorial Current. Strengthening of the winds in January 1977 terminates the 1976 event very rapidly. An estimate of the volume change of the warm upper layer gives a rate of 27×10^6 m^3 s^{-1} for the draining of warm water from the western Pacific Ocean over a one-year period. The 1976 El Niño event is concentrated predominantly north of the equator, in contrast to the 1972 event, and is terminated early by a renewed increase in the winds.

1. Introduction

In 1976 a moderately strong El Niño event occurred along the coast of Peru, as reported by Miller (1977). The event had a negligible effect on the Peruvian anchovy fishery, which had not recovered since the catastrophic 1972 El Niño. Along the coast of Peru, water temperatures were above average from February 1976 to January 1977, as indicated by the sea surface temperature anomalies at Puerto Chicama (Fig. 1).

A scenario for the occurrence of El Niño has been developed by Wyrtki (1975), explaining it as the response of the equatorial Pacific Ocean to atmospheric forcing. The necessary prerequisite is a period of excessively strong southeast trade winds along the equator during which warm water is accumulated in the western equatorial Pacific; at the same time the thermocline is depressed and sea level rises. The subsequent relaxation of the trade winds causes an internal wave that travels along the equator from the western Pacific to the east, which leads to the accumulation of warm water off Peru. The response of sea level during the 1972 El Niño event has been used to verify this theory (Wyrtki, 1977), and it has been established that the first peak in sea level along the coast of Peru is followed by a decline in sea level in the western Pacific lasting about one year, by a readjustment of the equatorial circulation, and by a second peak of sea level along the coast of Peru. The purpose of this study is to verify how well the 1976 event followed the suggested scenario.

2. The wind field

To discuss the atmospheric forcing, knowledge of the wind field for the period 1974–77 is required. Unfortunately, the wind observations made by merchant ships during this period are not yet available in a systematically collected and edited form and, consequently, one has to rely on the observations at Christmas and Canton Islands, shown in Fig. 1. In addition, cloud motion as observed by satellites allows the determination of wind vectors at the low cloud level, which may be used as an index of surface winds. Such an index for the area between 5°N and 5°S, 150°W and 180°W has been computed and has been made available through the courtesy of Professor James Sadler, University of Hawaii.

The three wind indices shown in Fig. 1 exhibit essentially the same behavior. Strong equatorial trade winds prevail during the second half of 1975. From December 1975 to January 1976 both the cloud motion winds and the winds at Christmas Island show a marked decrease, while winds at Canton Island remain strong. This decrease in the wind field probably triggered the 1976 El Niño event. After March, wind decreases further and remains weak during most of 1976. The meteorological records from Kwajalein and Truk also show that winds were weaker during the first eight months of 1976 than during the corresponding periods in 1975

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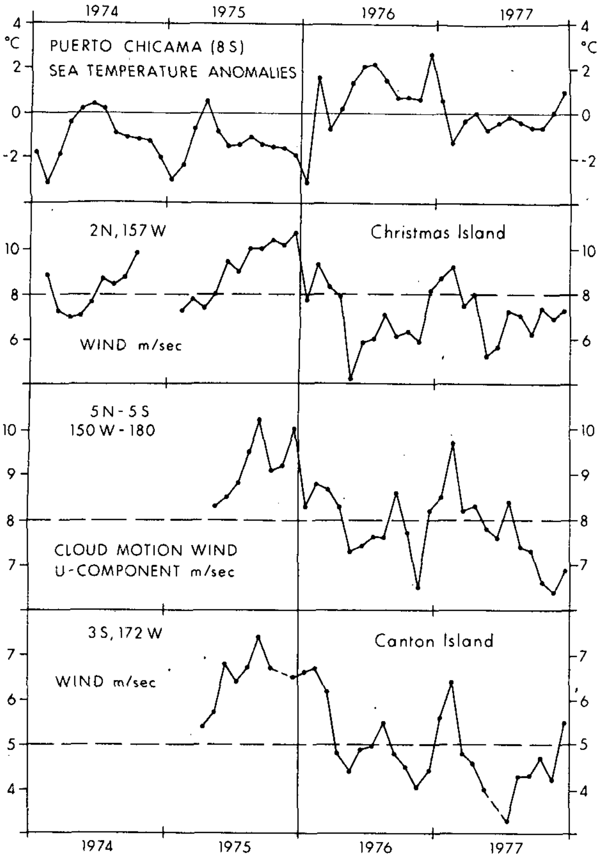

FIG. 1. Time series of monthly mean sea surface temperature anomalies at Puerto Chicama (Peru), of wind speed at Christmas and Canton Island, and of cloud motion winds over the central equatorial Pacific Ocean from 1974 to 1977.

and 1977. However, it should be noted that the seasonal wind maximum at these two stations is during the period December–April, while winds are very weak and variable during the remainder of the year. In 1976 this period of maximum wind was much shorter and winds were weaker. Trade winds along the equator increase again in January and February of 1977, but are weak during the remainder of the year. The similarity of the three wind records gives confidence that they properly represent the strength of the trade wind field in the central equatorial Pacific, which has been identified as responsible for the generation of El Niño.

3. Sea level 1974–77

Starting in 1974 a network of sea level stations has been established in the equatorial Pacific Ocean (Wyrtki, 1979). Records from the stations (Fig. 2) have been used to compute time series of monthly mean sea level which are used in Figs. 3 and 4 to illustrate the response of sea level during the 1976 El Niño event. The records are relative to the mean sea level at each station during the years 1974–77. The first important observation is the almost complete absence of an annual signal, and the prevalence of low-frequency fluctuations. An annual signal is apparent only at La Libertad (Ecuador) during 1974 and 1975. Also remarkable is the virtually constant sea level at Papeete from 1974 to 1976.

The strong winds in 1975 along the equator lead to strong equatorial upwelling, which lowers sea level at all equatorial stations from Nauru to Christmas Island (Fig. 4). The winds also cause an

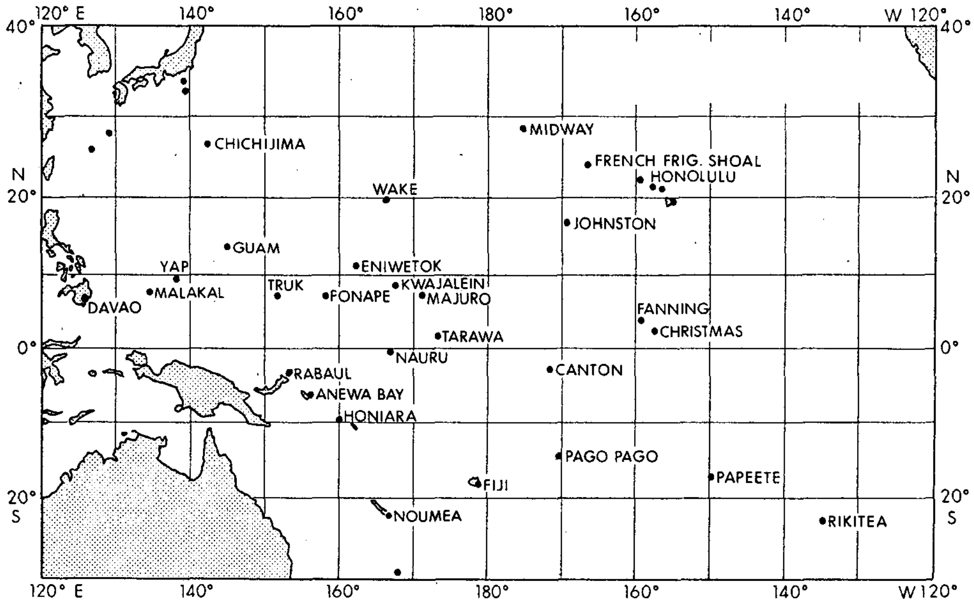

FIG. 2. Location of the sea level gages referred to in this study.

increase of sea level in the western Pacific, which is most pronounced in Yap and Davao and occurs somewhat later in Ponape and Honiara. At the same time, sea level is low at La Libertad. As sea level is ~12 cm higher in the western Pacific and 8 cm lower at the eastern side of the ocean, the east-west sea level difference has been increased by ~20 cm because of the strong winds in the second half of 1975. Immediately following the first relaxation of the equatorial trade winds in January 1976, sea level rises at La Libertad and drops in the western Pacific. At the same time, equatorial upwelling decreases and sea level at all equatorial stations rises to a normal level. The drop of sea level in the western Pacific occurs first at Yap and Davao, somewhat later at Ponape and last at Honiara. Sea level at La Libertad rises sharply from December to March and the first peak is reached in June, while lowest sea level in the western Pacific occurs only in the last quarter of 1976. This sequence of events in 1976 is essentially the same as that during the 1972 El Niño event.

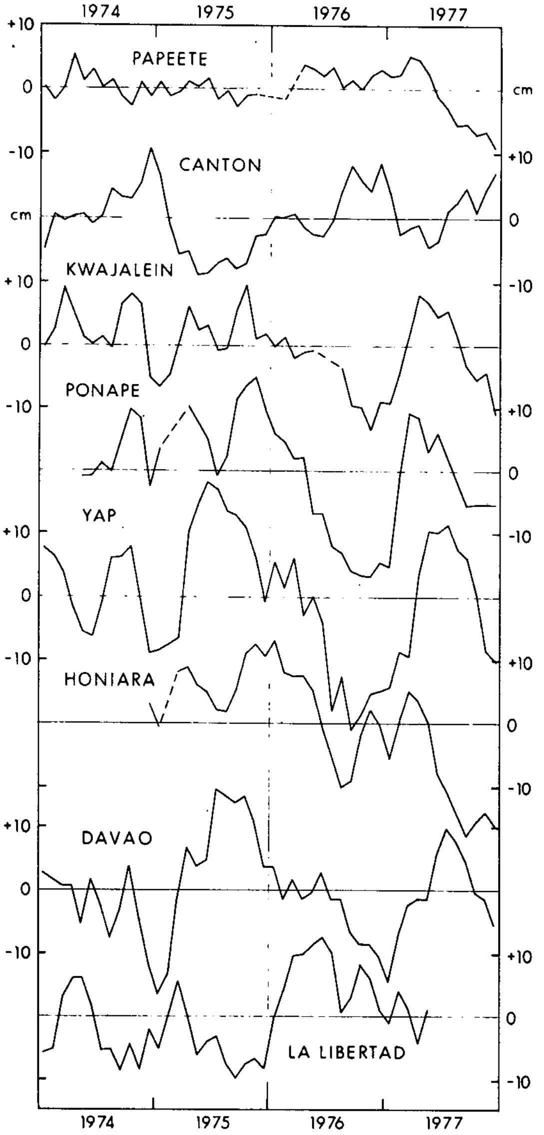

FIG. 3. Sea level variations (cm) during the 1976 El Niño event shown by time series of monthly mean sea level at selected stations from 1974 to 1977. For station locations see Fig. 2.

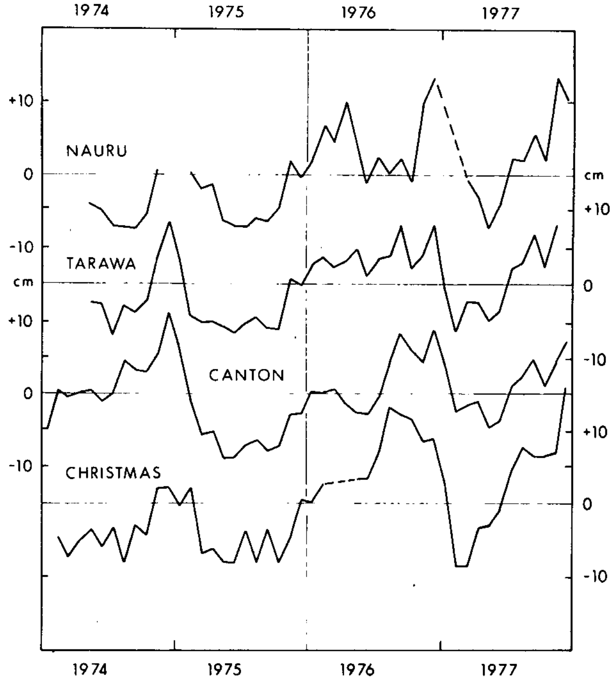

FIG. 4. Time series of monthly mean sea level (cm) at stations along the equator from 1974 to 1977.

In the second half of 1976 sea level at Kwajalein and Ponape reaches a low, while sea level at Canton and the other equatorial stations is high. This increase in the sea level difference across the North Equatorial Countercurrent indicates an intensification of the current. In 1972 the increase in the strength of the Countercurrent was followed by a second peak of sea level at La Libertad; such a peak is not observed there in 1976. At Puerto Chicama there is a second peak of temperature in December 1976 (Fig. 1), but the increase of the equatorial trade winds in January and February 1977 may have prevented the occurrence of the second peak in sea level at La Libertad. In fact, immediately after the increase in the equatorial winds, sea level rises rapidly at all stations in the western Pacific and the 1976 El Niño event is terminated.

There is another important difference between the events in 1972 and in 1976. The response of sea level in 1972 was strong both north and south of the equator as shown by the sea level record at Anewa Bay in the Solomon Islands (Wyrtki, 1977). During the 1976 event, sea level response in the

Southern Hemisphere represented by Honiara in the Solomon Islands is very weak and late. Consequently, one must conclude that the 1976 event was largely concentrated in the Northern Hemisphere. Unfortunately, the wind data are not sufficient to document clearly the difference in the development of the wind field during the two El Niño events.

4. Maps of sea surface topography

The network of sea level stations in the central and western equatorial Pacific allows the preparation of maps of the deviation of sea level from normal (Figs. 5 and 6). The normal is the mean sea level at each station during the four years 1974–77; the mean annual signal has not been removed. The amplitude of the mean annual signal is less than 5 cm in the entire area except near Japan. The time series of sea level shown in Figs. 3 and 4 clearly demonstrate that low-frequency events completely override the mean annual signal.

The maps of June and October 1975 (Fig. 5) show the buildup of sea level in the western equatorial Pacific preceding the 1976 El Niño event. The highest sea level is in the Philippine Sea and reaches to Guam. Sea level is higher than normal between 10°S and 20°N and west of 170°E. The high sea level values off Japan are a seasonal effect. Along the equator sea level is low, indicating strong equatorial upwelling. Sea level at La Libertad, which is far outside our maps, is shown by the circled number south of the equator on the eastern border of the map. It is lower than normal before the El Niño event. It should be pointed out that sea level at La Libertad is representative of sea level along the entire coast of Ecuador and northern Peru, as well as at the Galapagos Islands (Wyrtki, 1975, Fig. 2). The sea level records from Baltra in the Galapagos Islands are not useful after 1975 because of large gaps and uncertain reference levels. By October 1975 the buildup of sea level has increased and the area of abnormally high sea level extends to the Hawaiian Islands. The very high sea level (+15 cm) at French Frigate Shoals appears to be a local effect. Remarkable is the large horizontal coherence of sea level deviations. The high sea level along 10°N where the Countercurrent trough is located and the low sea level along the equator represent a weakening of the Countercurrent because of a decrease of the sea level slope across it. This weakening of the Countercurrent also contributes to the accumulation of warm water in the western Pacific.

In December 1975 sea level has dropped sharply near the Philippines and a high of sea level has started moving eastward into the area between Guam and Wake. Sea level at La Libertad is still low. Along the equator, sea level has returned to normal, indicating a decrease in upwelling and consequently a reduction of the winds. By March 1976 sea level at La Libertad has risen sharply from −8 to +10 cm, while the high of sea level in the western Pacific has disappeared. Sea level near Japan is seasonally low.

In June 1976 (Fig. 6) sea level has reached a peak of +12 cm at La Libertad, but is below normal throughout the western Pacific. The east-west sea level difference across the Pacific has decreased from ~60 cm in October 1975 to ~20 cm in June 1976, if a mean difference of 40 cm is assumed. By October 1976 the size of the sea level depression in the western Pacific has increased. Sea level is lower everywhere west of 170°E, but the largest depression is found along 10°N where the Countercurrent trough is situated. In contrast, sea level is high along the equator, and the increased sea level difference across the Countercurrent indicates that its flow is strong. It is interesting to compare the sea level topography of October 1976 with that of October 1975 in order to realize the dramatic reversal of the situation and the horizontal extent of the sea level changes. The draining of water from the western Pacific Ocean during this one year results in a drop of sea level by 20–30 cm over a large area. The associated water budget and its consequences will be discussed later.

By January 1977 the area of low sea level in the western Pacific has decreased somewhat and sea level at La Libertad has returned to normal. It should be noted that sea level response in the western Pacific during the 1976 event was largely restricted to the area north of the equator; the waters around the Solomon Islands responded only weakly to the event. This is another indication that each El Niño event will have somewhat different strength and characteristics.

The very rapid termination of El Niño is shown by the dramatic change of sea level topography from January to April 1977. Sea level in the western Pacific has risen above normal over a wide area, and has dropped along the equator. There seems to be little doubt that the change of sea level from January to April 1977 was the response to the stronger equatorial trade winds in January and February 1977 (Fig. 1).

5. An estimate of water transport

It seems appropriate now to estimate the volume of water involved in this event. Sea level in the western Pacific is highest in October 1975 preceding El Niño and is lowest one year later in October 1976. The change of sea level during this one year is mapped in Fig. 7 and shows a very coherent large-scale pattern. A maximum drop of 36 cm occurs at Truk, and a large area exhibits a change of more than

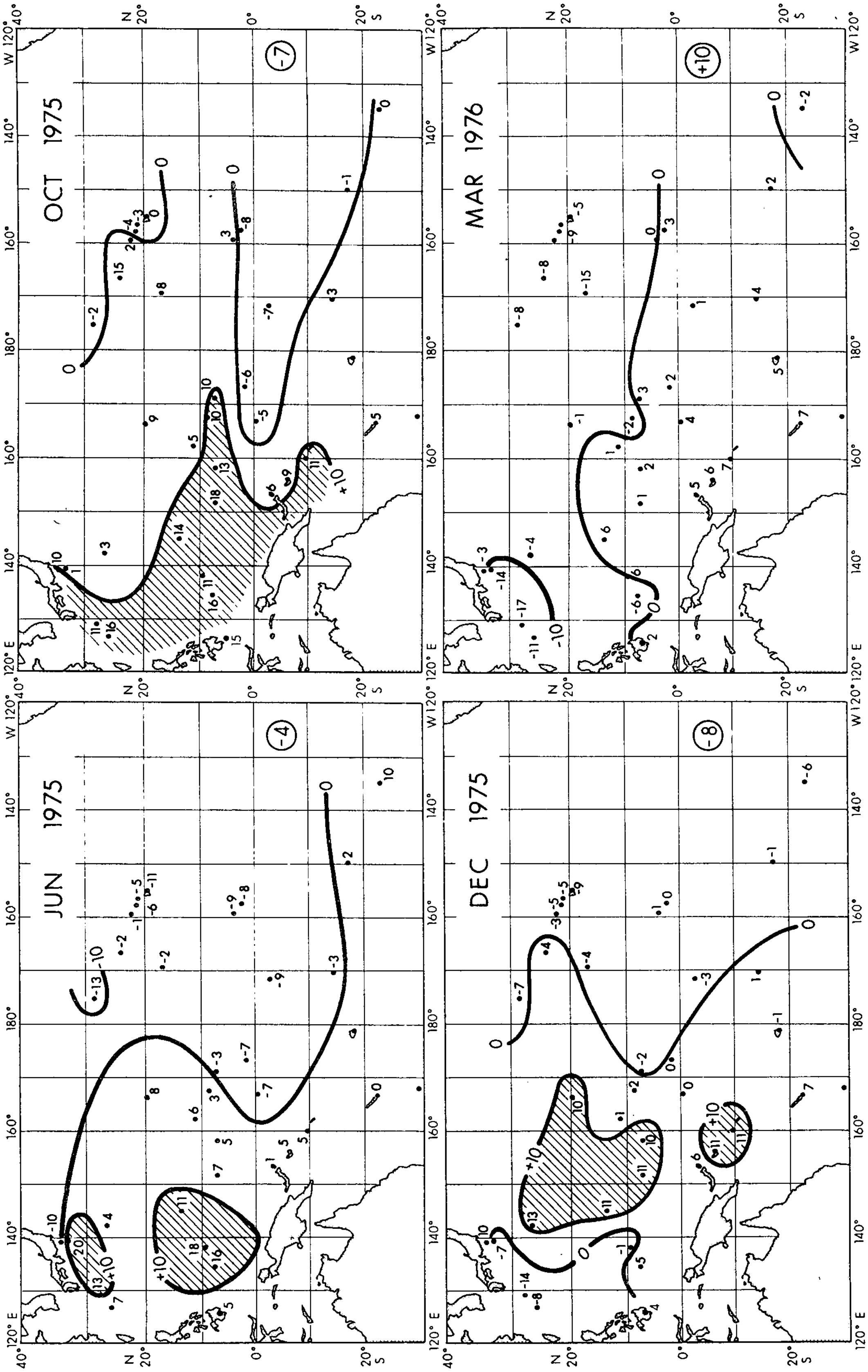

FIG. 5. Development of sea surface topography during the early part of the 1976 El Niño shown by maps of the deviation of monthly mean sea level from mean sea level during 1974–1977. The circled number at the right margin gives the sea level at La Libertad (Ecuador). Hatch marks indicate areas of highest sea level.

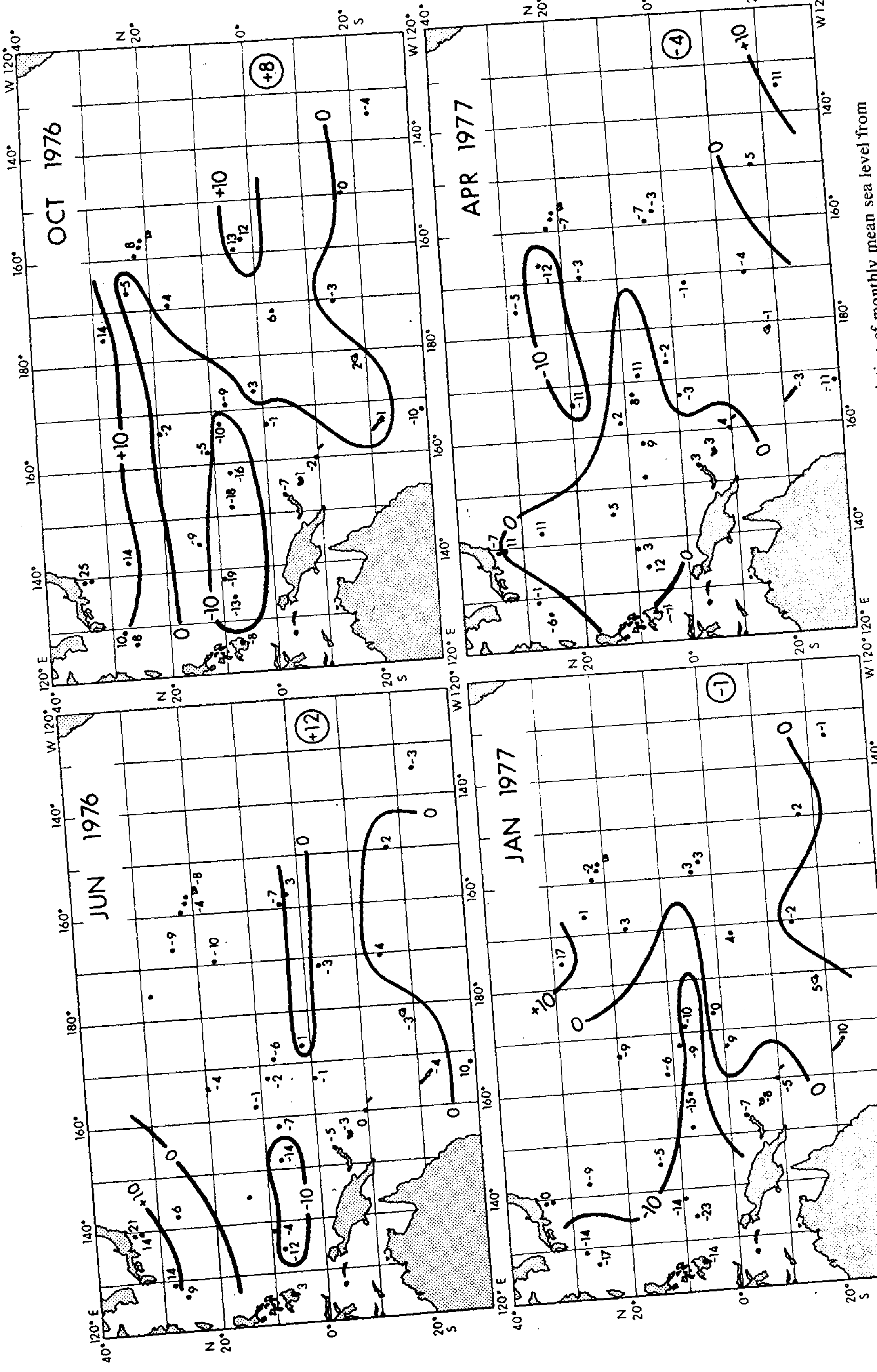

FIG. 6. Sea surface topographies during the late part of the 1976 El Niño event shown by maps of the deviation of monthly mean sea level from mean sea level during 1974–77. The circled number at the right margin gives the sea level at La Libertad (Ecuador).

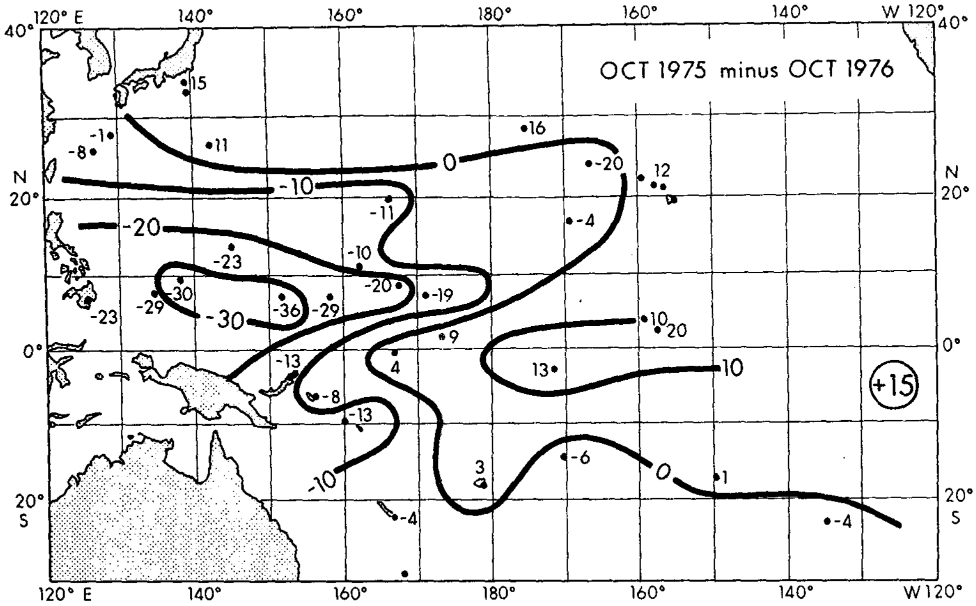

Fig. 7. The change of sea surface topography (cm) from October 1975 to October 1976. The circled number on the right margin gives the sea level change at La Libertad.

20 cm. The mean change of sea level in the area bounded by 20°N, the Philippines, New Guinea, 10°S, the zero line and the date line has been determined to average 17 cm over an area of 16×10^{12} m^2. The large change of -20 cm at French Frigate Shoals has not been included into the computation because it is largely the result of a very high value in October 1975, which is probably due to local wind effects.

The sea level change Δh, however, does represent a much larger change ΔD in the thickness of the warm upper layer, which is given by $\rho \Delta h = \Delta\rho \Delta D$, where $\Delta\rho/\rho$ is the relative density difference between the warm upper layer and the cold deep layer in a two-layer system. This relationship has been shown to exist in the equatorial Pacific, where Meyers (1979a) compared the mean annual variation of sea level and of the depth of the 14°C isotherm. Whereas the variation of sea level has an amplitude of $\sim$4 cm, that of the isotherm depth has an amplitude of $\sim$12 m, giving a value $\Delta\rho/\rho = 3.3 \times 10^{-3}$. Using this value and $\Delta h = 17$ cm, one obtains an average rise of the interface $\Delta D = 51$ m. This rise is much larger than the mean annual variation of the depth of the interface, which according to Meyers (1979b) has an amplitude of $\sim$10 m in the area concerned. The association between a decrease of sea level and a rise of the interface is real and has been documented by Masuzawa and Nagasaka (1975). They show that dynamic topography dropped by about 20 cm, while the 20°C isotherm rose by 50–80 m from January 1972 to January 1973 during the 1972 El Niño event along a repeated oceanographic section at 137°E. Their Fig. 2 also demonstrates that this rise is coherent over a large region from the equator to 17°N.

The actual volume of water that left the warm surface layer of the western Pacific Ocean from October 1975 to October 1976 can now be computed. It is given by the area of 16×10^{12} m^2 and the average rise of the interface by 50 m, resulting in a volume of 8×10^{14} m^3. Since this volume drained from the western Pacific during one year, or 3×10^7 s, the equivalent transport is 27×10^6 m^3 s^{-1}. Such a transport sustained during an entire year must have a pronounced effect on the strength of major ocean currents. Assuming that most of the water is involved in the internal wave between the western and the eastern Pacific and does not flow north into the Kuroshio, the water transport must be accomplished by a decrease of the westward flow in the South Equatorial Current, by an increase of the eastward transport in the South Equatorial Countercurrent, by an increase of the eastward transport in the North Equatorial Countercurrent and possibly by an increase of the Equatorial Undercurrent. The response of some of these currents during the 1972 El Niño event has been shown by Wyrtki (1977). In 1976 the increased strength of the North Equatorial Countercurrent is indicated by the increased slope of sea level between the equator and 10°N in the maps from June 1976 to January 1977. The higher sea level along the equator represents a weakening of the South Equatorial Current on both sides of the equator, and probably an increase in the South Equatorial Countercurrent. It should also be noted that an eastward flux of 27×10^6 m^3 s^{-1} during one year does not necessarily

TABLE 1. Drop of sea level (cm) during the 1972 and 1976 El Niño events.

Station	1972	1976
Guam	60	23
Anewa Bay	46	8
Truk	40	36
Kwajalein	28	29
Wake	20	10

transport water all the way from the western to the eastern Pacific. If the flux is distributed evenly over 20° of latitude and 150 m of depth, the average velocity is only 9 cm s^{-1} and the distance traveled by a water particle during one year is 2700 km or about 25° of longitude. This estimate of the volume changes of the upper layer of the ocean over a large area indicates quite clearly that the time variability of major ocean currents can be accounted for by vertical displacements of the thermocline, a result obtained earlier for the equatorial jet in the Indian Ocean (Wyrtki, 1973). It also demonstrates that a temporary increase of the transport of a major ocean current can be accomplished by vertical movements of the thermocline at the origin and terminus of the current, and does not necessarily involve an increase of the transport in an entire gyre.

6. Discussion

The analysis of the sea level data indicates that two time scales are associated with the event. The first, of the order of 50–100 days, represents the time from the first relaxation of the wind stress to the first peak of sea level at the coast of South America; it is essentially the travel time of an internal Kelvin wave across the Pacific Ocean along the equator (Hurlburt *et al.*, 1976; McCreary, 1976).

The other time scale, of the order of a year, represents the subsequent draining of the warm upper layer of the western Pacific described in this article. The same year-long drop of sea level was also associated with the 1972 El Niño event (Wyrtki, 1977). This one-year-long decrease of sea level in the western Pacific has also been modeled by McCreary (1977, Fig. 3.2), who extended his earlier calculations to 278 days. At that time his model thermocline had risen by 60 m in the western Pacific, with a maximum rise near 10°N and 10°S, and had dropped along the equator, with a maximum depression at the eastern boundary. This is indeed similar to the observed changes of sea level shown in Fig. 7, if one notes that a drop in sea level corresponds to a rise in thermocline depth. The rise of the thermocline in McCreary's model extends to 20° of latitude and is largest near 10° of latitude, which implies that all equatorial currents will be affected by the year-long drop of sea level in the western Pacific. In fact, the largest gradient in the anomalous thermocline topography shown by McCreary (1977, Fig. 3.2) is between 5° and 10° of latitude in the central part of the ocean. This gradient constitutes an intensification of the equatorial Countercurrents in both hemispheres. It would be interesting to verify the topography of the thermocline computed by McCreary in the eastern Pacific, also, but unfortunately there are no islands there on which sea level gages could be installed to determine the horizontal extent of this internal wave and its amplitude away from the coast.

Common to both the 1972 and the 1976 El Niño is also the sudden end of the event. Sea level drops along Peru and Ecuador and along the equator; it rises very rapidly in the western Pacific. Equatorial winds become strong again between December 1976 and February 1977, first at Christmas Island and later at Canton (Fig. 1). Sea level drops sharply and virtually simultaneously at all equatorial stations from December to February; the greatest drop is from January to February (Fig. 4). In the western Pacific, sea level rises equally rapidly, but somewhat later. From January to February a sharp rise is observed at Ponape and Kwajalein, both situated in the Countercurrent trough. Simultaneously a first rise occurs at Davao. The rise at Yap follows between March and April (Fig. 3). This termination of the El Niño event happens within two to three months and with a time scale similar to that of its onset.

It has been suggested by the reviewers that this termination phase of El Niño is simply the reverse of the initiation phase. While linear theory may support such a view, it seems to me that the thermocline in the tropical ocean has sufficiently large horizontal gradients and that the equatorial currents have sufficiently large vertical shear to require a more complex model and a complete simulation of the termination phase. In fact, the response of the sea surface and of the ocean thermal structure during El Niño look very much like a large internal seiche along the equator.

Like other natural events, El Niño appears in different strength and shape, as recently pointed out by Quinn *et al.* (1978). He rates El Niño events from 1 (very weak) to 4 (strong); the 1972 event rates 4 and the 1976 event rates 3, medium. This differentiation appears also in the sea level changes (Table 1). Data from the few stations where sea level was recorded during both events clearly demonstrate that the 1972 event was much stronger and that the 1976 event occurred largely in the Northern Hemisphere. It is impossible to analyse the reasons for this different behavior without a much better knowledge of the tropical wind field. This deficiency in our knowledge may soon be removed when cloud motion vectors observed by satellites will become available also for the western Pacific Ocean. The 1976 event was also terminated earlier than the 1972 event, by a renewed increase of the equatorial trade winds. The principal ocean response during the two events was essentially the same, however.

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