Sea Level During the 1972 El Niño[1]

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ABSTRACT

Sea level records at many island and coastal stations in the equatorial Pacific Ocean have been used to study its response and that of the associated equatorial circulation to the 1972 El Niño. The response can be divided into five phases. Preceding El Niño, stronger than normal equatorial trade winds cause a buildup of sea level in the western Pacific in 1970 and 1971. After the wind strength peaks, sea level begins to drop slowly in the western Pacific. The first collapse of the wind field is followed by high sea level along the eastern border of the ocean, actually initiating El Niño off Peru. The initial oceanic response seems to consist of an equatorial Kelvin wave, which has been successfully modeled by others, and a strong reduction of the South Equatorial Current. During the third phase sea level drops very rapidly in the western Pacific, the equatorial trough is being filled, the South Equatorial Current retreats to the south of the equator, and the Countercurrent intensifies. Then follows a second peak of sea level along the eastern side of the ocean including the coast of Central America and extremely low sea level in the western Pacific. Thereafter, conditions return to normal, and sea level changes are even more rapid than at the onset of El Niño. The development of a weaker event in 1975 is also analyzed, and it is shown that such an event terminates after the second phase.

1. Introduction

A new scenario about the onset of El Niño, developed by Wyrtki (1975b), explains it as a dynamic response of the equatorial Pacific Ocean to atmospheric forcing. It is claimed that El Niño is preceded by excessively strong southeast trade winds over the central Pacific, which intensify the South Equatorial Current and lead to an accumulation of warm water in the western Pacific and to an increase in the east–west slope of sea level. As soon as the wind stress in the central Pacific relaxes, the accumulated water tends to flow back, increasing the strength of the eastward flowing branches of the circulation and decreasing the strength of the South Equatorial Current. This response of the ocean leads to a deepening of the warm surface layer along the eastern side of the ocean and to the well-known consequences of El Niño. The initial oceanic response seems to take the form of an equatorial Kelvin wave and has been numerically simulated by Hurlburt *et al.* (1976) and by McCreary (1976). These models have indicated that the response is very fast, on the order of 50–100 days. The scenario was based on the analysis of comprehensive wind data for the period 1950–72, but on rather limited observations of sea level; consequently it seems advisable to study the sea level response in more detail and with the intent to learn more about the phase relations between the winds, the sea level and the response of the circulation. Variations of sea level during El Niño have been noted and discussed before by Bjerknes (1966) and Hickey (1975), but they have not developed a coherent scenario of the sequence of events by which winds, sea level and circulation are coupled.

Because of the collapse of the Peruvian anchovy fishery, El Niño of 1972 has received considerable attention and the oceanographic and meteorological conditions during its occurrence have been described in some detail. Wooster and Guillen (1974) describe surface temperature and salinity conditions in the waters off South America and state that in January 1972 the pattern of surface temperature was not conspicuously different from the average distribution. Miller and Laurs (1975), in a month-by-month description of the temperature field in the entire tropical Pacific Ocean, state that the first signs of warming were indicated in February 1972, and that substantial widespread warming was noticeable only in March 1972. Ramage (1975) discusses the meteorological situation chiefly on the basis of clouds and rainfall, and states that the near-equatorial trade winds weakened as usual in April 1972 but then remained weak until the following April. Because his statements about the winds are indirectly obtained, one cannot easily use them to study phase relations with sea level. The quarterly maps of circulation anomalies at 700 mb prepared by Krueger and Winston (1975) also cannot

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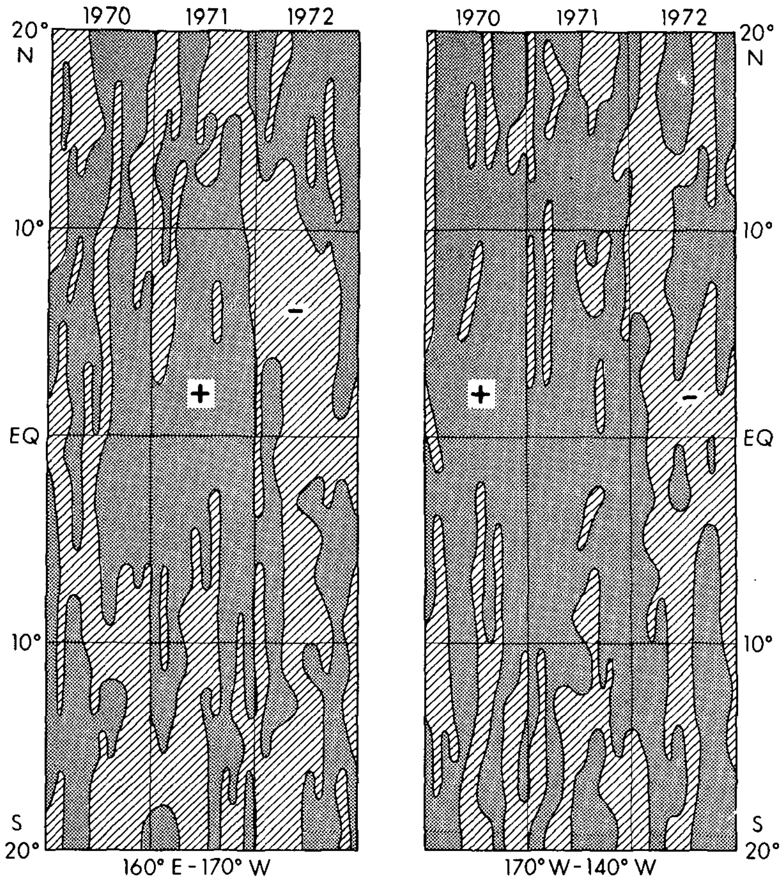

FIG. 1. Deviation of the east-west component of the wind stress during the years 1970–72 from the average annual cycle (1950–72) between 20°N and 20°S over the central Pacific Ocean between 160°E to 170°W (left panel) and 170°W to 140°W (right panel). Data were averaged for intervals of 2° of latitude; only the sign of the deviation is given, + designating east winds stronger than normal.

be used to study such phase relations, although they clearly document the weakening of the tropical circulation over the Pacific during 1972.

2. The wind field

The surface winds over the tropical Pacific Ocean have been investigated for the period 1950–72 by Wyrtki and Meyers (1975, 1976) based on direct observations collected by merchant ships. Unfortunately, in 1973 the National Oceanic and Atmospheric Administration discontinued the archiving of this data set. This action caused a considerable decrease in the number of observations available for 1972, which is apparent from the large data gaps in the bimonthly wind maps prepared by Wyrtki and Meyers (1975). Data on winds derived from cloud movements as observed by satellites were not yet available for the central and western Pacific during 1972 and thus could not be substituted for the missing ship observations.

A good correlation between the strength of the trade winds and the occurrence of El Niño has been found for the area between 4°N and 4°S, 140°W and 180° (Wyrtki, 1975b, Fig. 4). Barnett (1977), analyzing the same data set by means of empirical orthogonal functions, finds that the first anomaly pattern of the east-west component of the wind is best related to El Niño events. This eigenvector has a maximum amplitude between about 6°N and 10°S, 140°W and 160°E. A correlation of the wind field with the southern oscillation index (Quinn, 1974) has also been made and indicates that it is highest in the same area.

The wind data from Wyrtki and Meyers (1975) have been used to compute anomalies of the zonal component of the wind stress for two areas, 160°E–170°W and 170°–140°W, at intervals of 2° of latitude and for each month of the period 1970–72 (Fig. 1). North of 10°N and south of 10°S the wind field fluctuates between positive and negative anomalies, with typical time scales of one to five months. In the equatorial region a different pattern exists, which has much longer time and larger space scales. Two periods can readily be recognized: a positive anomaly in 1970 and 1971, and a negative anomaly in 1972. In the western Pacific, between 160°E and 170°W, the stronger than normal trade winds last from August 1970 to December 1971 and extend from about 10°N to 6°S. In the central Pacific, between 170° and 140°W, the size as well as the duration of the strong trade winds is even larger. They start in February 1970, last until February 1972, and extend from about 14°N to 10°S.

This period of abnormally strong trade winds is followed by a period of much weaker winds in 1972. Starting in December 1971 west of the dateline and near 10°N, trade winds become weaker than normal. In January trade winds in the western Pacific are weaker than normal everywhere to the west of 170°W, but are still strong in the central Pacific. The area of weaker trade winds extends progressively southward and eastward. By March winds over the entire central and western Pacific are well below normal. In the western Pacific the weakening of the trade winds is most pronounced between the equator and 10°N, and in the central Pacific between 6°N and 6°S. Based on this analysis it is not possible to give a definitive date for the collapse of the trade wind system at the onset of the 1972 El Niño, but it can be stated that the weakening of the wind system started in December 1971 in the western equatorial Pacific and had spread over the entire western and central Pacific by March. The weakening of the trade wind field during El Niño does not take place in the core regions of the trade wind field, but is associated with a retreat of the trade winds from the western equatorial Pacific. As stated by Wyrtki and Meyers (1975) the area of ocean covered by trade winds is largest preceding El Niño and smaller during El Niño.

A much more detailed analysis of the sequence of meteorological events connected with the 1972 El Niño is presently being undertaken by Colin Ramage at the University of Hawaii, and through his courtesy some of his data were used to prepare a time series of the zonal component of wind stress for the area between 4°N and 4°S, 140°W and 180°, covering the entire El Niño period (Fig. 2). This time series, an extension of the series shown by Wyrtki (1975b, Fig. 4), shows the period of very strong equatorial trade winds lasting from December 1969 to February 1972 for 27 consecutive months. During this time the average zonal wind stress of 0.85 N m^{-2} is 44% larger than the long-term mean wind stress of 0.059 N m^{-2}. Taking $\sigma/N^{\frac{1}{2}}$, where σ is the standard deviation of a sequence of N values, as the accuracy of the mean value, it can be stated that the long-term mean is accurate to 2% and the mean during the 27 very windy months is accurate to 4%. Consequently, the wind stress during 1970 and 1971 was significantly larger than the mean wind stress.

In March 1972 wind stress suddenly decreases substantially and remains much below normal during the remainder of 1972. In January 1973 equatorial zonal wind stress is again higher than normal and remains so during all of 1973. It is important to note that El Niño was preceded by a very long period of extremely strong trade winds near the equator, that the collapse of the wind field was very sudden locally but started at different times in different areas, and that the period of weak equatorial trade winds in 1972 was immediately followed by abnormally strong trades in 1973.

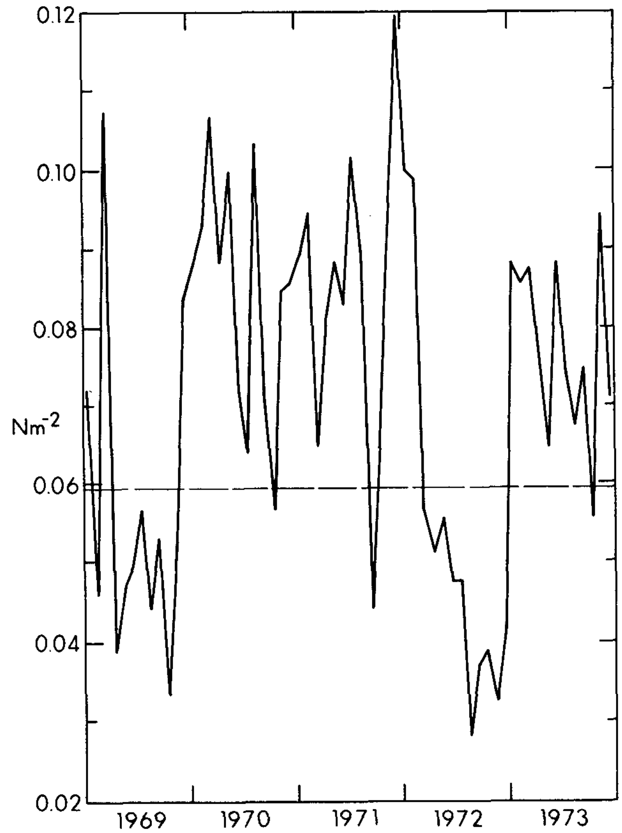

FIG. 2. Time series of the east-west component of the wind stress over the central Pacific Ocean between 4°N and 4°S and between 140°W and 180°. The dashed line gives the long-term mean wind stress of 0.059 N m^{-2}.

3. The response of sea level

To study the response of the sea surface topography to atmospheric forcing during the 1972 El Niño, time series of sea level at several locations in the equatorial Pacific Ocean are shown in Figs. 4, 5 and 6. The location of the observing stations is shown in Fig. 3. The time series in Fig. 4 are based on values of daily mean sea level, while those in Figs. 5 and 6 use monthly means; all curves are displayed relative to the long-term mean at each station. A comparison between the curves for Anewa Bay and Baltra shown in both figures demonstrates that the use of monthly means is appropriate to the time and space scales involved, although variations of shorter periods but smaller amplitude are present. Sea level has also been used to compute indices for the

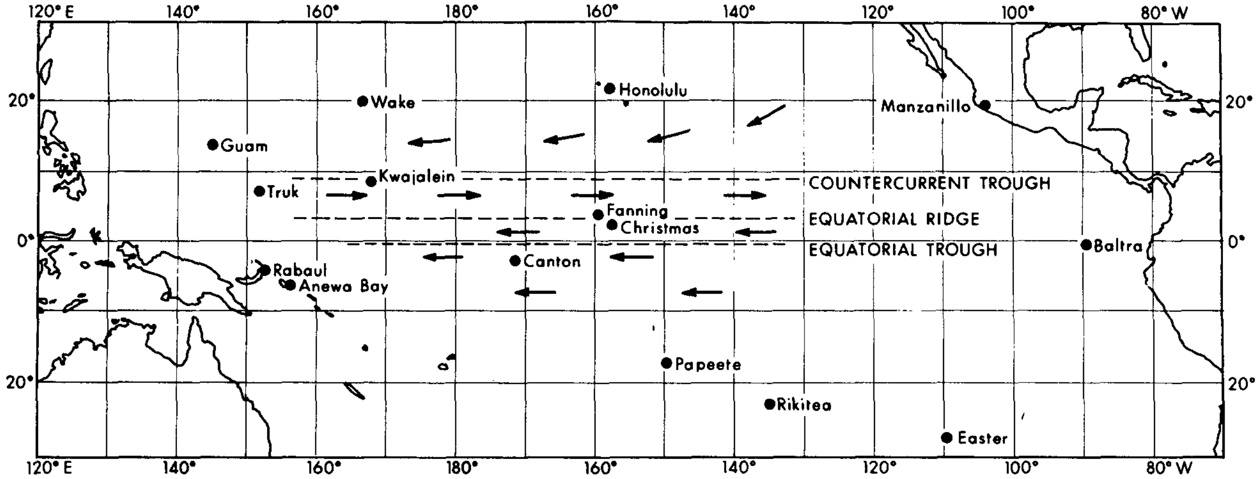

FIG. 3. Locations of the sea level gages from which data were used in this study. The major equatorial currents, topographic ridges and troughs are also indicated.

strength of the equatorial currents in the central Pacific according to the method developed by Wyrtki (1974). This study uses the mean dynamic topography of the sea surface relative to 500 db averaged between 140°W and 170°E and disturbs this mean profile by the monthly mean sea level observed at several island stations. The technique results in time series of the height of sea surface topography at the various ridges and troughs associated with the equatorial currents (Fig. 7) and in time series of sea level differences across the major currents, representing indices of their strength (Fig. 8).

The variation of sea level during the 1972 El Niño is most strikingly displayed in Fig. 4 by the records of

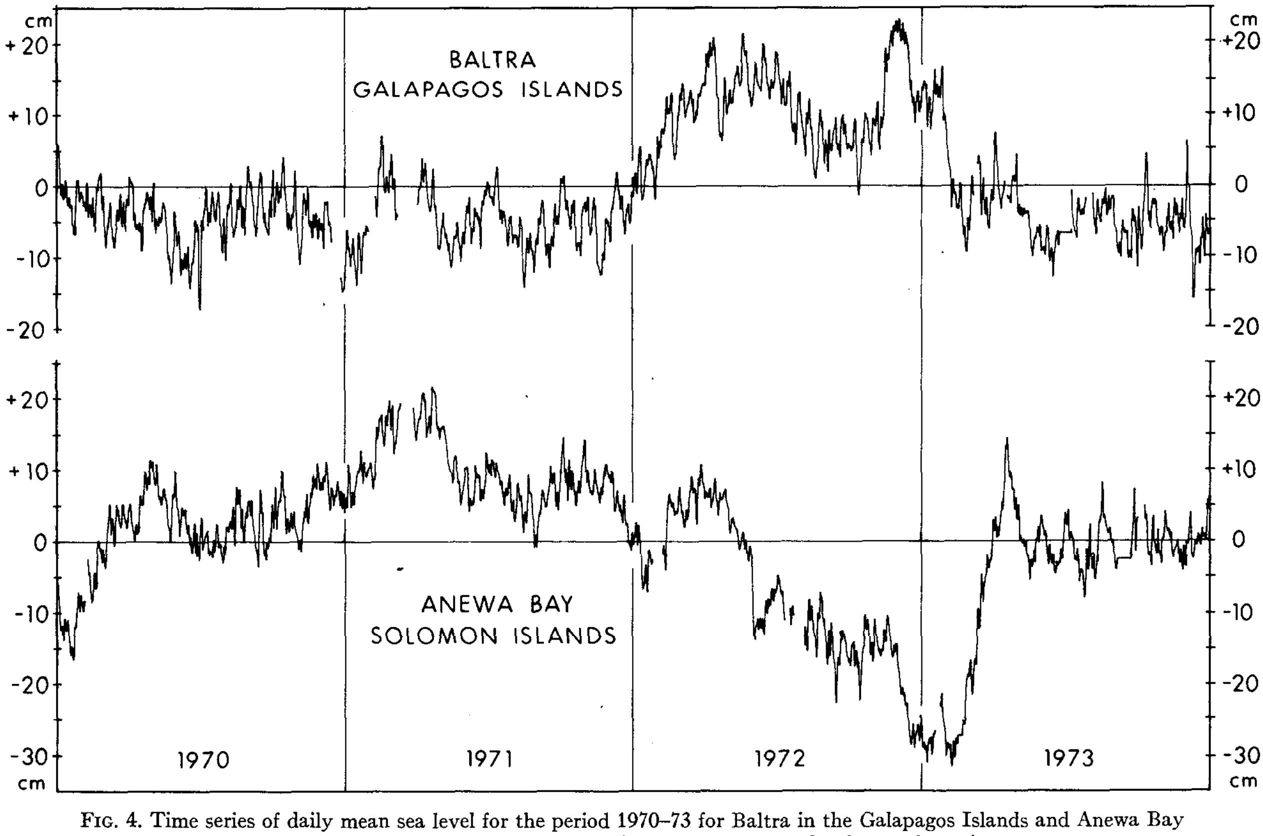

FIG. 4. Time series of daily mean sea level for the period 1970–73 for Baltra in the Galapagos Islands and Anewa Bay in the Solomon Islands relative to the long-term mean sea level at each station.

Anewa Bay in the Solomon Islands and of Baltra in the Galapagos Islands, on both sides of the equatorial Pacific. In 1971 before El Niño, sea level is high at Anewa Bay and low at Baltra. From May 1971, sea level drops in the west, first slowly, later rapidly, reaching a low in January 1973. In contrast, sea level at Baltra does not start to rise before December 1971, rises very rapidly until April 1972, drops again, and reaches a second peak in December 1972. Thereafter, sea level at both locations returns rapidly to near normal. While these two records describe the principal response of the ocean, much more can be learned by the

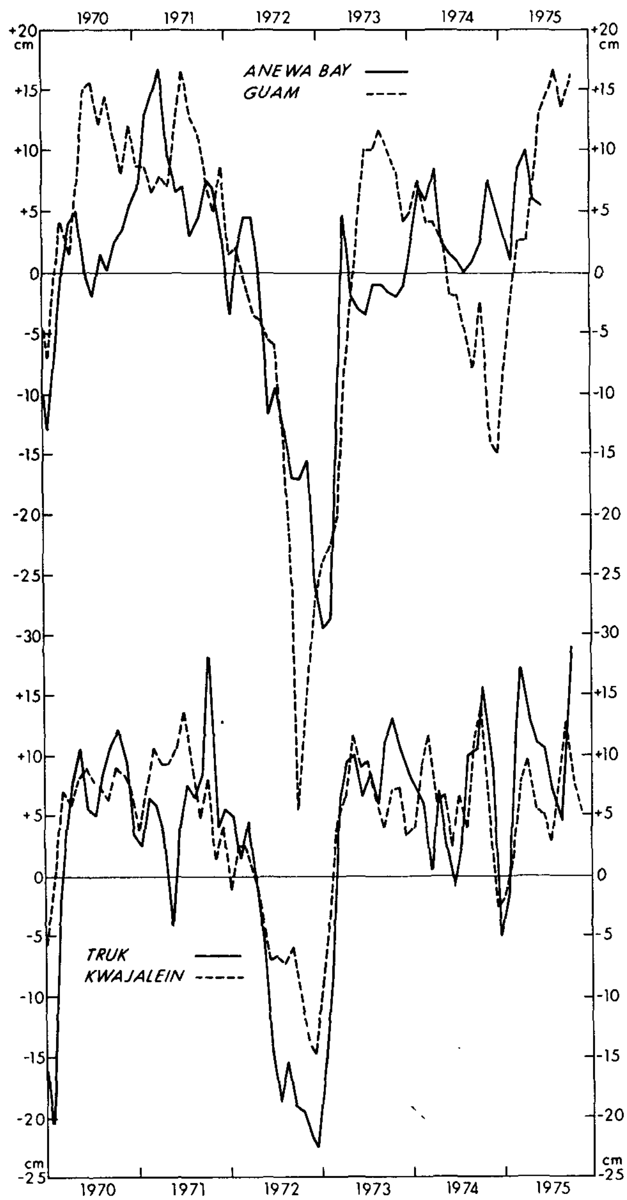

Fig. 5. Monthly mean sea level at four stations in the western Pacific Ocean from 1970–75 relative to the long-term mean sea level at each station.

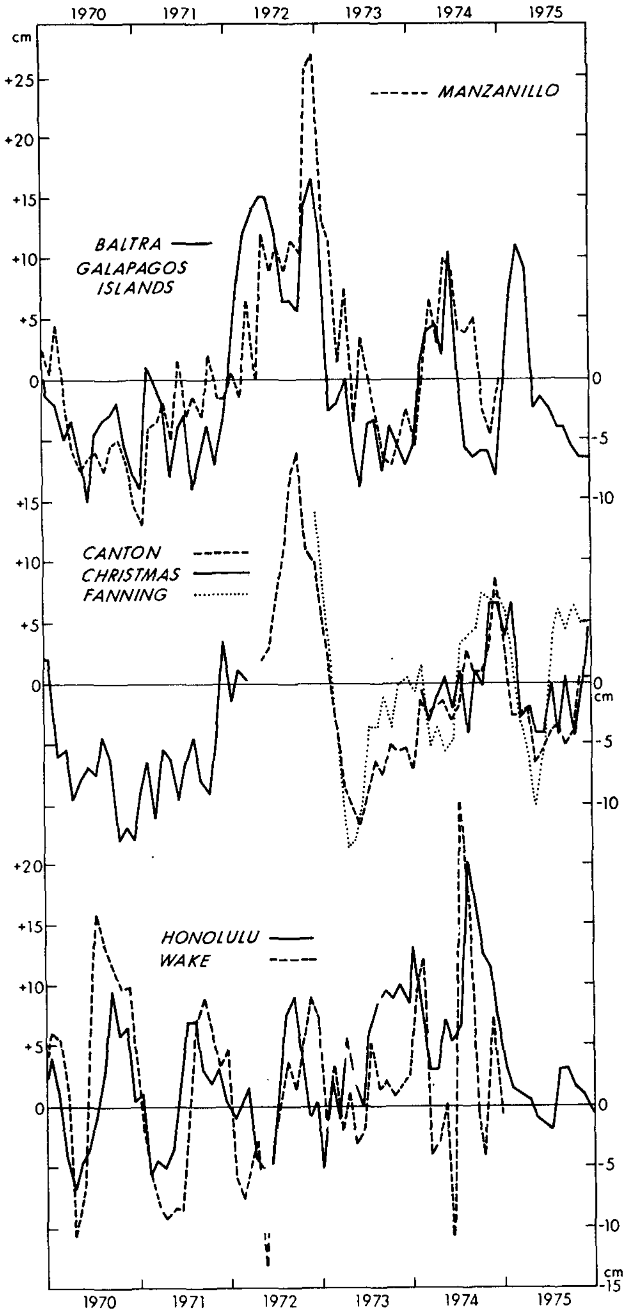

Fig. 6. Time series of monthly mean sea level at several stations in the Pacific Ocean from 1970–75 relative to the long-term mean sea level at each station. For locations see Fig. 3. For Manzanillo the anomaly of sea level is shown after elimination of the long-term annual signal.

study of records from other stations and by comparing the response of the various current indices.

In 1970 and 1971 when the trade winds are much stronger than normal over the central equatorial Pacific (Fig. 2), sea level in the western Pacific is abnormally high. Maximum sea level, about 15 cm above the mean, is reached in April 1971 at Anewa Bay,

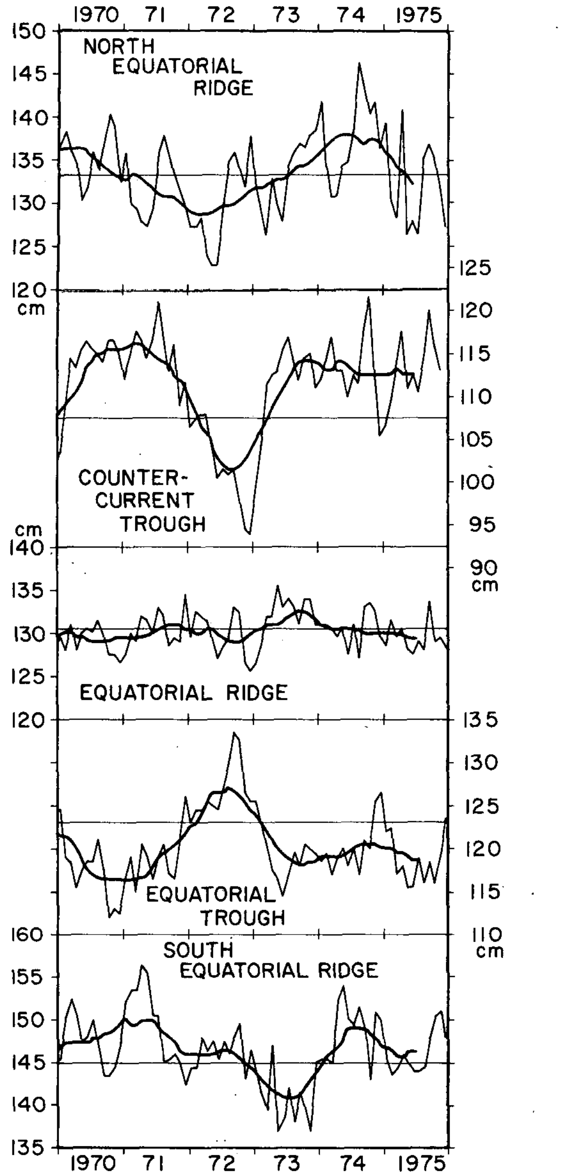

FIG. 7. Time series of sea level height at ridges and troughs associated with the equatorial circulation, 1970–75. The thin curves give monthly averages, the heavy curves the 12-month running means.

in July in Guam and Kwajalein, and in October in Truk (Fig. 5). In contrast, sea level at the Galapagos Islands and at Christmas Island is 5–10 cm lower than normal, indicating strong upwelling along Peru and along the equator (Fig. 6). At all these stations the mean annual variation of sea level has an amplitude of only about 5 cm, which is often barely recognizable in the records and is usually concealed by larger irregular variations. The fact that sea level at stations along the coast of Peru and Ecuador follows the same pattern as that at Baltra has been established (Wyrtki, 1975b, Fig. 2).

During the time of strong southeast trades in 1970 and 1971 the south equatorial ridge is intensified and the equatorial trough is deepened (Fig. 7), making the South Equatorial Current much stronger than normal (Fig. 8). At the same time, sea level in the Countercurrent trough is high, implying a weak Countercurrent and a weak North Equatorial Current. During the entire period from March 1970 to June 1971 the trade winds over the Countercurrent are much stronger than normal (Wyrtki and Meyers, 1975) and probably lead to an intensification of the east-west slope of sea level and consequently to higher sea level in the Countercurrent trough in the western Pacific.

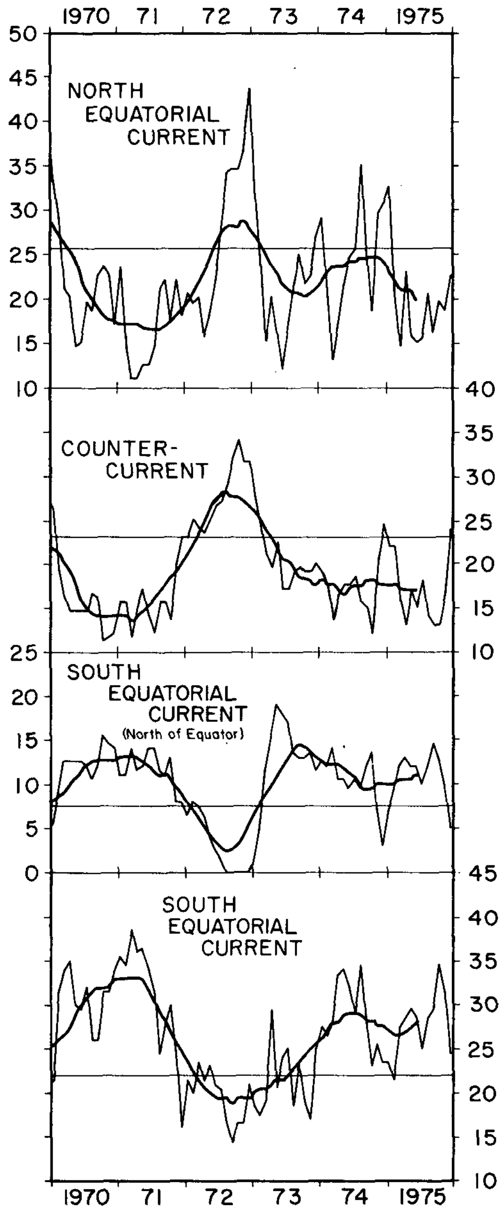

FIG. 8. Time series of sea level differences (cm) across zonal currents in the central equatorial Pacific, 1970–75. The thin curves give monthly averages, the heavy curves the 12-month running means.

After its peak in 1971, sea level in the western Pacific decreases, first slowly and in several steps and later in a rather accelerated fashion until the minimum is reached. By April 1972 sea level at the four stations shown in Fig. 5 has dropped about 15 cm and has fallen below mean sea level. At the same time, sea level at Baltra has been rising by 34 cm from a minimum of −12 cm on 22 November to a peak of +22 cm on 12 April 1972. This shows that during the early phase of the 1972 El Niño, sea level in the western equatorial Pacific drops rather slowly, while its rise along the eastern boundary is rapid. The same pattern seems to occur during the 1957 and the 1965 El Niño, as can be seen from the sea level records shown by Bjerknes (1966) and Hickey (1975), although they had no records from the Solomon Islands. Events during 1972 seem to be typical for El Niño in general.

The response of the equatorial currents to these sea level changes is very interesting. During the second half of 1971, sea level at the south equatorial ridge decreases and the equatorial trough fills rapidly from October to December 1971, thus decreasing the strength of the South Equatorial Current (Fig. 8). The model computations by Hurlburt *et al.* (1976, Fig. 1) even show a reversal of the equatorial flow. During the same period the Countercurrent trough deepens, which leads to an increase of the Countercurrent to approximately normal strength. Since the height of the north equatorial ridge also decreases following its normal annual cycle, the North Equatorial Current does not increase but remains weak.

In April, when the peak of sea level is reached in the east, sea level in the western Pacific takes another, even more decisive drop. At Truk sea level drops by 23 cm from March to July; at Anewa Bay the drop is 22 cm from April to September; and the most spectacular drop occurs at Guam, where sea level drops by 38 cm from July to October. The drop in sea level at Kwajalein is only 15 cm and more gradual. The lowest sea level is reached at Guam in September, at Kwajalein and Truk in December 1972, and last at Anewa Bay in January 1973. The catastrophic consequences of this extraordinary drop in sea level on marine life in Guam have been described by Yamaguchi (1975).

During this time, sea level at the Galapagos Islands and along the coast of Peru and Ecuador remains abnormally high, although there is a seasonal drop from August to October (Fig. 6), coinciding with the Southern Hemispheric winter and the period of lower sea surface temperatures. It should, however, be noted that this drop in sea level might not be caused by the simultaneous drop in sea temperature. Coinciding with the drop of sea level in the western Pacific, sea level rises near the equator, filling the equatorial trough, as shown in Fig. 6 by the observations at Canton, which fortunately were resumed at about the same time that the observations at Christmas stopped. Because of the very high coherence of monthly mean sea level at the two stations (Wyrtki, 1973), observations from either station may be used for our analysis.

The decisive drop of sea level in the western Pacific from March to December 1972 is also reflected in drastic changes of the equatorial currents. While the south equatorial ridge remains at a normal level, the equatorial trough fills rapidly in the second half of 1972, leading to a decrease of the South Equatorial Current below its normal strength. The filling of the equatorial trough also leads to the disappearance of the sea level slope between the equatorial trough and the equatorial ridge near 4°N. This implies that there is no westward flow north of the equator and that the Countercurrent probably extends southward to the equator. This finding, based on sea level observations, is confirmed by an analysis of transequatorial temperature sections (Wyrtki *et al.*, 1977). A corresponding oceanographic situation observed during the 1957 El Niño has been described by Austin (1960).

Sea level in the Countercurrent trough decreases throughout 1972 (Fig. 7), increasing the sea level slope across the Countercurrent, which in the second half of 1972 becomes much stronger than normal. The drop of sea level in the Countercurrent trough coincides with the seasonal rise of sea level at the north equatorial ridge and consequently the North Equatorial Current is abnormally strong in the second half of 1972. While before El Niño, during the buildup of high sea level in the western Pacific, the South Equatorial Current was strong and the Countercurrent and the North Equatorial Current were weak, the situation is now exactly reversed: the two North-Hemispheric currents are strong and the South Equatorial Current is weak.

The weakening of the South Equatorial Current and the intensification of the eastward flowing Countercurrent during the second half of 1972 apparently lead to the second peak in sea level at Baltra in December 1972 (Fig. 6). It should also be noted that the rise in sea level during El Niño is not restricted to the Southern Hemisphere but is also observed along the coast of Central America. An example is sea level at Manzanillo (Fig. 6), which is abnormally high from May 1972 to April 1973, with a peak of +27 cm in December 1972. At Manzanillo it is necessary to consider the anomaly of sea level, because the mean annual signal has an amplitude of 10 cm and is very regular. This affirms the earlier analysis (Wyrtki, 1973) that strong flow in the Countercurrent is followed by anomalously high sea surface temperatures off Central America, which should be related to an accumulation of warm water and to an increase in sea level.

In January and February 1973 conditions at all locations return rapidly to normal: sea level in the western Pacific rises and sea level along South and

Central America, as well as along the equator, drops. First sea level drops at Baltra by 26 cm in one month (Fig. 4) and along the coast of South America (not shown). About one month later it rises in the western Pacific. This rise of sea level is even more rapid than its earlier drop. At Anewa Bay sea level rises by 40 cm within only two months. During the same time, sea level drops along the equator in response to the increasing strength of the trade winds (Fig. 2). This is related to a reappearance of strong equatorial upwelling and to the disappearance of the warm temperature anomaly along the equator (Miller and Laurs, 1975). The equatorial currents respond accordingly: the North Equatorial Current and the Countercurrent decrease in strength, and the South Equatorial Current increases to normal levels.

In order to contrast the behavior of sea level during El Niño at stations in the equatorial belt with stations outside, the sea level records of Honolulu and Wake are included (Fig. 6). It is quite apparent that the large disturbance in sea level is not found at these two stations near 20°N, and that the mean annual signal is prevailing, except for a disturbance in 1974, well after the El Niño event. An inspection of the monthly sea level records of Papeete, Rikitea and Easter Island (not shown; for station location see Fig. 3) also shows no signs of a response of sea level to the 1972 El Niño. This implies that the response of sea level to an El Niño event is restricted to the equatorial region, at least in the central parts of the ocean.

In 1973 the southeast trade winds became very strong again and sea level resumes a pattern similar to that in 1970 and 1971. Sea level is above normal in the western Pacific and below normal along the eastern side of the ocean and along the equator. The South Equatorial Current increases in strength and the two North Hemispheric currents are weaker than normal. This situation lasts through 1974 and is then disturbed by another, but weak, El Niño event in early 1975 (Wyrtki *et al.*, 1976). During this weak event sea level drops at Guam, Truk and Kwajalein, but not at Anewa Bay (Fig. 5); the minimum is reached in December. At the same time a maximum of sea level occurs at the equator, as shown by the records of Christmas Island, Canton and Fanning (Fig. 6). The peak of sea level at Baltra occurs in March 1975 after a steady rise starting in December 1974. During this weak event there is no second sea level maximum and no very deep drop of sea level in the western Pacific. This analysis indicates that sea level is a very sensitive indicator of the strength of an El Niño event.

4. Discussion and conclusions

Based on the foregoing analysis, the response of sea level during a major El Niño event can be divided into five phases:

1) The buildup of sea level in the western equatorial Pacific.
2) The first relaxation leading to a slow drop of sea level in the west and a first peak in the east.
3) The rapid drop of sea level in the west and the filling of the equatorial trough while sea level remains above normal in the east.
4) The minimum of sea level in the west and the second peak in the east.
5) The equalization: a very rapid increase of sea level in the west and a drop in the east and along the equator, returning sea level to normal.

This sequence of events is related to the response of the equatorial circulation. During the buildup phase caused by very strong and lasting southeast trade winds which penetrate far into the western equatorial Pacific, the South Equatorial Current is strong, transporting more warm water than usual into the western equatorial Pacific. At the same time the North Equatorial Current and the Countercurrent are weak due to high sea level in the Countercurrent trough. Apparently the Countercurrent does not drain enough water from the western Pacific, so that sea level also rises there. This phase must last for more than a year to build the necessary potential for an El Niño event. It is very likely that the intensity of this buildup phase determines most decisively the intensity of the following El Niño event.

As soon as the buildup phase has reached its peak there is a tendency for the potential energy accumulated in the western Pacific to force an equalization of sea level. This will happen with the first relaxation of the wind field. If the wind field relaxes very slowly, the relaxation of sea level might also occur very gradually and might not lead to the extreme fluctuations observed in 1972. In fact, the relaxation of the wind field may happen very suddenly over a period of only two or three weeks when the trade wind field near the equator effectively collapses; such an occurrence will not be adequately represented by monthly mean wind fields. The collapse of the wind field will then trigger an equatorial Kelvin wave, as modeled by Hurlburt *et al.* (1976) and McCreary (1976). This wave results in a very rapid rise of sea level in the east, as shown in these models by the corresponding depression of the depth of the thermocline. The bulk of the rise in sea level takes place over a period of two to three months, which is consistent with a response time scale of 50 to 100 days by the models, and is determined by the dynamics of an equatorial Kelvin wave. During this phase, sea level in the west decreases only slowly, probably because of the great accumulation of warm water over a wide area, which needs considerable time to drain. The response of the equatorial currents is also slow; the South Equatorial Current decreases; the Countercurrent increases to normal strength; and the

North Equatorial Current remains weak. This second phase may be as short as three months, according to the travel time of the Kelvin wave, but in 1971/72 it lasted about eight months.

While a minor El Niño event like that in 1975 might stop at this point, in a major event the collapse of the trade wind system is followed by a long period of weak trade winds and leads to a further drop of sea level in the western Pacific, which now happens at an accelerated rate. During this third phase in the response of sea level, the equatorial trough is being filled; the South Equatorial Current decreases further and disappears north of the equator. At the same time the Countercurrent becomes wider, probably stretches south to the equator, and intensifies. This situation leads to little change in sea level along the coast of South America, where sea level remains abnormally high in spite of a weak seasonal dip. Most of the changes now take place north of the equator, where the intensified Countercurrent transports water into the region off Central America and causes a rise of sea level. This phase lasts for about six months.

Phase four signals the culmination of the entire process. Lowest sea level in the western Pacific is reached about simultaneously with the second peak of sea level in the east along Peru. The mean east-west slope of the dynamic topography relative to 1000 db between the coast of Peru and the Solomon Islands is about 50 cm, according to Wyrtki (1975a). During phase four, sea level is 15 cm higher than normal at Baltra and along the coast of Peru, and 30 cm lower at Anewa Bay, virtually wiping out this mean east-west slope. Such a disappearance of the east-west slope of sea level during the 1957 El Niño has first been pointed out by Bjerknes (1966).

Phase 5 constitutes a rapid recovery of the system to its normal conditions. Sea level drops along Peru and along the equator and rises in the western Pacific. The equatorial currents return to normal. This rapid return to normal and the slight "overshooting" in 1973 is caused by the sudden onset of the very strong trade winds during that year.

Summarizing, one may conclude that the response of the equatorial Pacific Ocean to a decrease of the trade winds after a period of abnormal strength takes place first along the equator possibly by an equatorial Kelvin wave. The South Equatorial Current decreases, and sea level rises along the coast of Peru. If the decrease of the trade winds is prolonged, a second reaction follows, a filling of the equatorial trough, an intensification of the Countercurrent, and a second peak of sea level not only along Peru but also along Central America. Simulation of the entire sequence of events during El Niño will require a much more comprehensive modeling effort than previously made.

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