El Niño—The Dynamic Response of the Equatorial Pacific Ocean to Atmospheric Forcing[1]

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ABSTRACT

El Niño is the occasional appearance of warm water off the coast of Peru; its presence results in catastrophic consequences in the fishing industry. A new theory for the occurrence of El Niño is presented. It is shown that El Niño is not due to a weakening of the southeast trades over the waters off Peru, but that during the two years preceding El Niño, excessively strong southeast trades are present in the central Pacific. These strong southeast trades intensify the subtropical gyre of the South Pacific, strengthen the South Equatorial Current, and increase the east-west slope of sea level by building up water in the western equatorial Pacific. As soon as the wind stress in the central Pacific relaxes, the accumulated water flows eastward, probably in the form of an internal equatorial Kelvin wave. This wave leads to the accumulation of warm water off Ecuador and Peru and to a depression of the usually shallow thermocline. In total, El Niño is the result of the response of the equatorial Pacific Ocean to atmospheric forcing by the trade winds.

1. Introduction

El Niño is the occasional appearance of excessively warm water off the coast of Peru during the beginning of the year. It coincides with the Southern Hemispheric summer, with the season of weaker winds and the time of reduced upwelling. As such it would be a normal annual event, but in certain years, most recently in 1957–58, 1965–66, and 1972–73, the warm water accumulation is excessive, upwelling apparently ceases completely, the fish stock disappears or is at least no longer available to the fisherman, and the coastal birds, dependent on fish for food, die in large numbers, leading to decimation of the bird population. In total, El Niño amounts to a natural catastrophe.

The appearance of warm water is not an isolated local effect, but is coupled and coincides with changes in the ocean-atmosphere system over the entire equatorial Pacific as shown by Bjerknes (1966). The southeast trade wind system is weaker, the intertropical convergence zone is displaced southward toward the equator, and torrential rains occur over the normally dry coastal areas of northern Peru. All these events seem to be related to an eastward displacement of the low pressure system normally found over Indonesia (Ramage, 1975).

2. The regular seasonal cycle

Originally the name El Niño was applied to a weak coastal current flowing southward along the coast of Ecuador around Christmas time. As such it is an annual event and the current is weakly indicated on the maps of average surface currents for December and January compiled by Wyrtki (1965). During southern summer from December to March, the southeast trade winds off Peru are generally weaker (Wyrtki and Meyers, 1975) and the sea surface temperatures are higher (Wyrtki, 1964). The upwelling off Peru is strongest in southern winter when winds are strongest. At the same time temperatures are lowest as a result of seasonal cooling and intense upwelling.

In southern summer the offshore waters warm considerably and more so than the coastal waters. Under normal conditions a strip of cold water due to upwelling is present throughout the summer along the coast. Southeast of the Galapagos Islands a pool of warm water of more than 25°C develops in January and increases in temperature to 27°C in March (Wyrtki, 1964). From this warm pool a tongue of warm offshore water extends southeast as far as 20°S. The development of this warm water is most likely due to increased isolation, because the heat loss due to evaporation varies little throughout the year (Wyrtki, 1966).

As a consequence of this mean annual cycle the hypothesis has been developed by Bjerknes (1961) that very weak trade winds in certain years would lead to a cessation of upwelling, would allow the warm offshore water to approach the coast, and would permit the normal El Niño current to penetrate farther to the south. In all, a strong El Niño would represent nothing but an amplification of the summer warming. The basis of this hypothesis, in particular the presence of

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very weak southeast trades off Peru during El Niño, has not, however, as yet been tested.

3. El Niño conditions

Sea surface temperature is the most widely used indicator of El Niño, and indeed the changes are dramatic. Sea surface temperature at Puerto Chicama (7°S) during the last four El Niño events is shown in Fig. 1 together with its mean seasonal variation. Corresponding temperature patterns are found at all stations along the coast of Peru as shown by Wooster and Guillen (1974). The most striking features of these patterns are:

1) The extremely sudden rise of temperature at the onset of El Niño.
2) The repetition of the event in two successive years.
3) The return to almost normal conditions in late winter between the two temperature maxima.

In all, the temperature curves demonstrate that El Niño is an event which lasts for about 16 months, namely for two summers and one winter. The first peak in temperature is not always the highest, but apparently the longest. As indicated by surface temperature anomalies, El Niño may start as early as October (1940) or as late as March (1972).

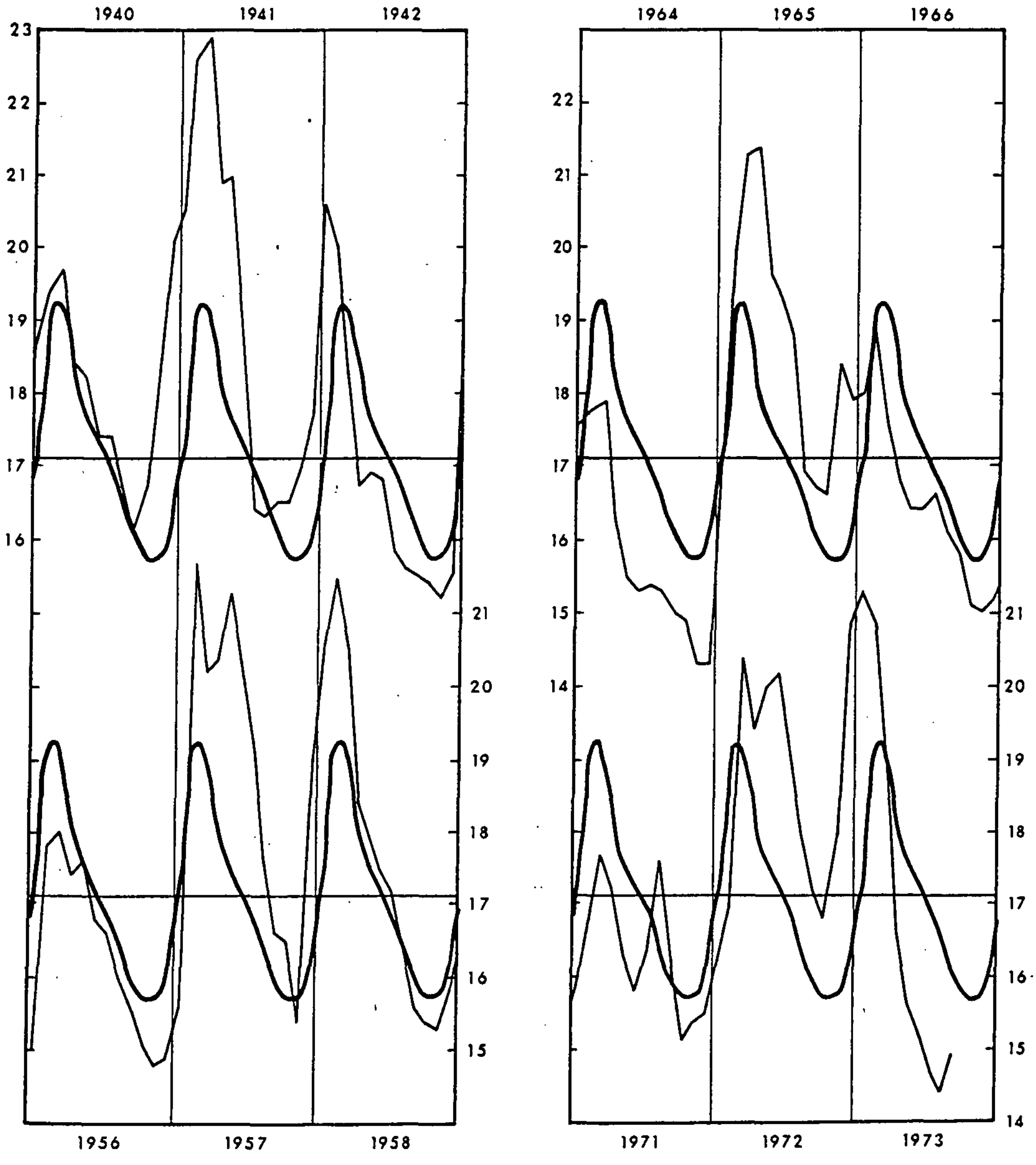

Fig. 1. Sea surface temperature (°C) at Puerto Chicama (7°S) during the last four El Niño events. The thin line gives observed monthly mean temperature, the heavy line the mean annual variation (1925–1973).

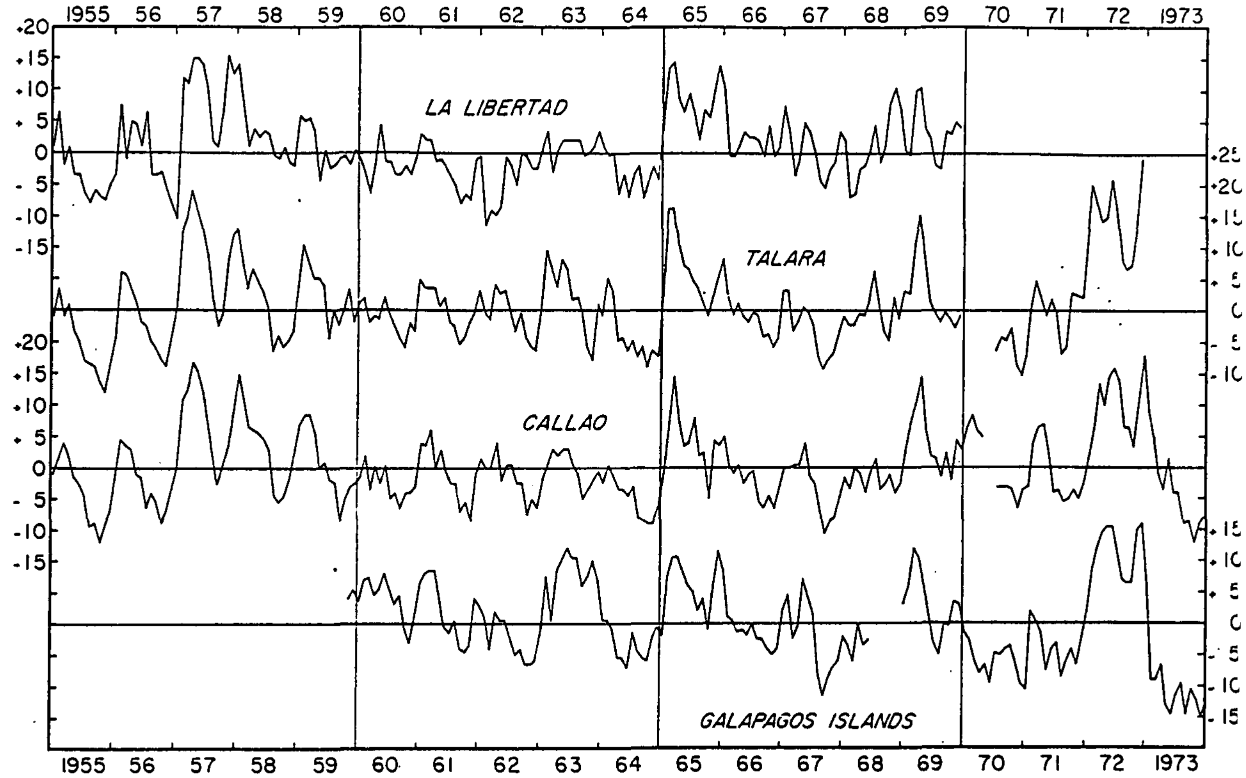

FIG. 2. Monthly mean sea level (cm) at La Libertad (2°S), Talara (5°S), Callao (12°S), and at the Galapagos Islands from 1955 to 1973.

Sea level along the coast behaves very similarly, as seen from Fig. 2. Essentially the same pattern of sea level fluctuations is present at La Libertad (2°S), Talara (5°S) and Callao (12°S), and also at the Galapagos Islands 1000 km offshore. Sea level rises as rapidly as temperature; it also has two peaks in successive summers and a characteristic drop in the intervening winter. One might assume that sea level along the coast responds to the warming of the nearshore waters. A rise of sea level by 15 cm due to a rise of temperature by 3°C implies that temperature in a 200 m thick layer must be raised by this amount. While it is usually assumed that El Niño consists of a thin layer of warm water flowing over the upwelling area (Wooster and Guillen, 1974), this calculation demonstrates that the thermal structure must be changed to appreciable depth during such an event. This concept will be discussed in Section 9.

4. The winds off Peru

Although a weakening of the southeast trades alone is held responsible for the occurrence of El Niño, and especially for the cessation of upwelling, by past investigators (Bjerknes, 1966; Wooster and Guillen, 1974), observational evidence of this is lacking.[2] It is true that winds off Peru are weaker in summer than in winter, and that this cycle is rather regular. In this section it will be shown that the southeast trade winds off Peru are not abnormally weak during times of El Niño, and therefore its occurrence must be explained by some other factor or factors.

When analyzing the trade wind field of the Pacific Ocean as well as its fluctuations during the period from 1950 to 1972 on the basis of ships observations, Wyrtki and Meyers (1975) developed time series of the wind and the wind stress for many areas. Direct wind observations by ships have been used, because winds inferred from gradients of atmospheric pressure are unsuitable at low latitudes, within about 15° from the equator. The time series of wind stress components for the area between 10°S, 20°S, 80°W, and the coast of South America is shown in Fig. 3; the individual monthly mean wind stress vectors are based on between 30 and 120 observations per month. Because the series composed of the individual monthly means is rather noisy, 5-month and 12-month running means are shown in Fig. 3. The 5-month running mean emphasizes the seasonal signal, while the 12-month running mean eliminates the seasonal signal and shows the long-term trend.

In the period from 1960 to 1970 the seasonal signal is particularly pronounced and regular. It is the same for the north-south as for the east-west components, indi-

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[2] *Editors note:* A pertinent paper by Hickey (1975), which does show such evidence, appeared while this paper was in press.

cating that the wind stress direction is rather constant but that the magnitude varies seasonally. An abnormal situation occurs when the southeast trades fail to weaken in the summer of 1956–57 and the mean stress is abnormally high. Also in 1971–72 the summer wind minimum fails to develop in the normal fashion. In contrast, winds in 1965 are rather normal. The same trend and detail of the wind stress time series is found in the 10° square to the northwest, indicating that the situation is not restricted to a small area, but represents the wind pattern over the entire region in which El Niño occurs. Also the charts of the 700 mb circulation anomaly by Krueger and Winston (1975) show that the southeast trades during the period from December 1971 to February 1972 were strong from the coast off Peru to about 120°W and weaker in the central and western Pacific.

Charts of the observed winds during oceanographic cruises in the coastal region off Peru and Ecuador for the years 1964, 1965, and 1966 have been published by Stevenson *et al.* (1970). A comparison of the three maps for the cruises in February–March of each year shows clearly that winds in 1965 were stronger than in 1964 or 1966, demonstrating that coastal winds during the 1965 El Niño were stronger than in other years. Consequently, one must abandon the idea that winds off Peru are abnormally weak during the period of El Niño, and one must search for other ways to explain this phenomenon.

5. Wind and temperature along the equator

The southeast trade winds always cross the equator into the Northern Hemisphere, and it is established that the near-equatorial convergence zone is shifted only about 3° latitude closer to the equator during El Niño (Ramage, 1975). It has also been shown that surface temperatures along the equator are anomalously high during El Niño (Bjerknes, 1966, 1972), although a weak equatorial temperature minimum is retained, as can be seen in the monthly surface temperature maps published by the National Marine Fisheries Service (1971–73). Along the equator upwelling takes place, and its intensity is believed to be related to the strength of the zonal wind. Surface temperature is a good indicator for the intensity of the upwelling, and consequently warmer equatorial surface temperatures should indicate a decrease in the intensity of upwelling and should correlate with weaker zonal winds.

The zonal component of the wind stress along the equator over the eastern and central Pacific Ocean is shown in Fig. 4 in the form of a time series of the 5-month and the 12-month running means. A striking difference between these two regions is clearly apparent. A seasonal signal is only weakly developed, especially in the central Pacific. The mean wind stress is almost twice as large (0.06 N m^{-2}) in the central Pacific as in the eastern part (0.035 N m^{-2}). The long-term fluctua-

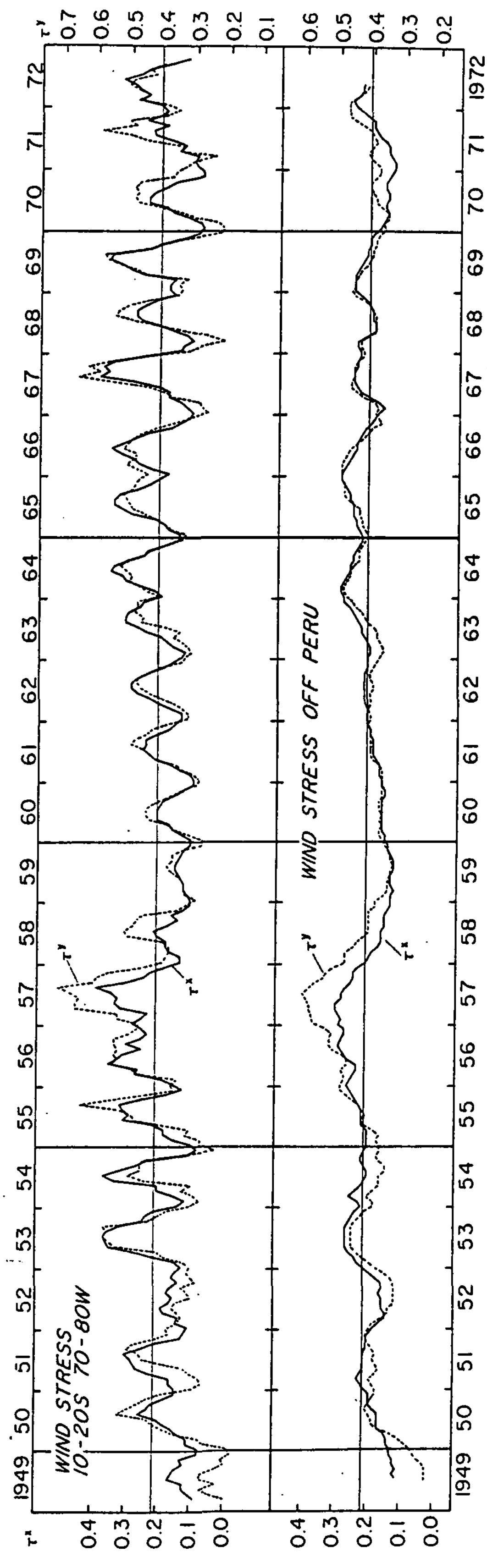

Fig. 3. Wind stress off Peru, 1949–1972; 5-month running mean (upper panel) and 12-month running mean (lower panel). τ^x is positive to the west, τ^y positive to the north, both in 0.1 N m^{-2}.

tions are much more pronounced in the central than in the eastern equatorial Pacific. The more striking events occur in 1955–56, when winds were very strong along the entire equatorial belt, and again in 1970–71, when they were especially strong in the central Pacific. Both these events were followed by a decrease of wind stress and by the occurrence of El Niño. Also in 1964, winds over the central equatorial Pacific were abnormally strong, and this event was followed by the moderately strong El Niño in 1965. No apparent reaction was caused by the weaker peaks in wind stress occurring in 1960 and 1967.

In addition, the monthly mean surface temperatures at Canton Island (3°S, 172°W) are shown in Fig. 4, and they dramatically demonstrate the relationship between strong zonal winds and increased upwelling as indicated by lower surface temperatures as previously shown by Bjerknes (1972) and by Hires and Montgomery (1972). It should, however, be noted that weaker winds in the central equatorial Pacific occur about simultaneously or slightly after El Niño has commenced. This is true in 1957, 1965 and 1972. The fact that surface temperature rises before the winds decrease is also apparent from the figure shown by Bjerknes (1972), who uses individual monthly averages. This fact needs further study and explanation. It should also be noted that maximum temperatures at Canton Island occur near the end of El Niño, and are consequently a result of the meteorological conditions during El Niño, and not a cause for its occurrence.

6. The southeast trade winds

We have just seen that El Niño is preceded by strong trade winds in the central equatorial Pacific, and therefore it seems appropriate to investigate the behavior of the entire southeast trade wind field. In Fig. 5 the time series of the zonal component of the wind stress is given for six areas between the equator and 20°S and between 90°W and the dateline, covering most of the southeast trade wind field. For each area the 5- and 12-month running means are shown. An inspection of the six curves shows that fluctuations in the strength of the southeast trade winds are generally not coherent over their entire area. In the easternmost areas, between 90°W and 120°W, seasonal variations dominate the picture, and long-term departures are relatively small. It should be noted that the zonal winds were strong during both the 1957 and 1972 El Niño in the area between the equator, 10°S 90°W, and 120°W. This area is closest to the area off Peru, for which we made the same statement earlier, and demonstrates clearly that the southeast trades during El Niño are stronger rather than weaker over a large area seaward from Peru. Also in the area between Tahiti and Fiji (10°S to 20°S and 150°W to 180°W) the seasonal cycle is dominant.

The remainder of the southeast trade wind field, and in particular its central portions, does not have a very pronounced seasonal cycle, but long-term fluctuations are dominant. Most outstanding is the period of strong winds in 1955–56 which occurred in the entire

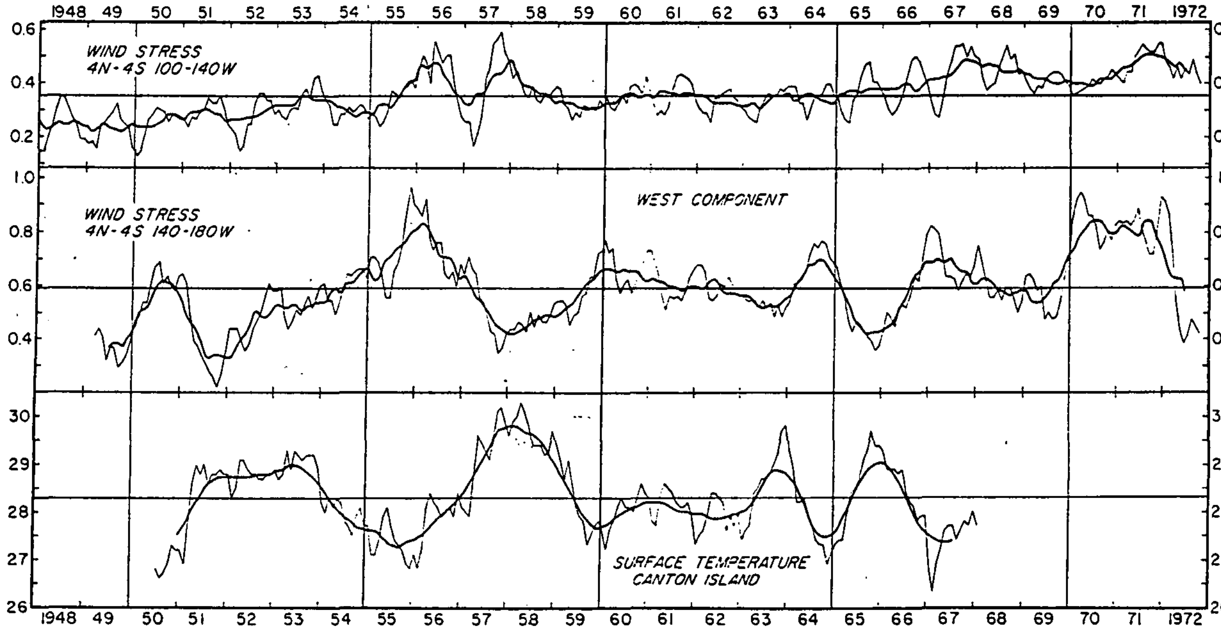

FIG. 4. Zonal component of the wind stress in the equatorial Pacific from 1948 to 1972 (in 0.1 N m^{-2}, positive to the west) and surface temperature (°C) at Canton Island (3°S, 172°W). Heavy lines give the 12-month running mean, thin lines give the 5-month running mean for the wind stress and individual monthly temperatures for Canton Island.

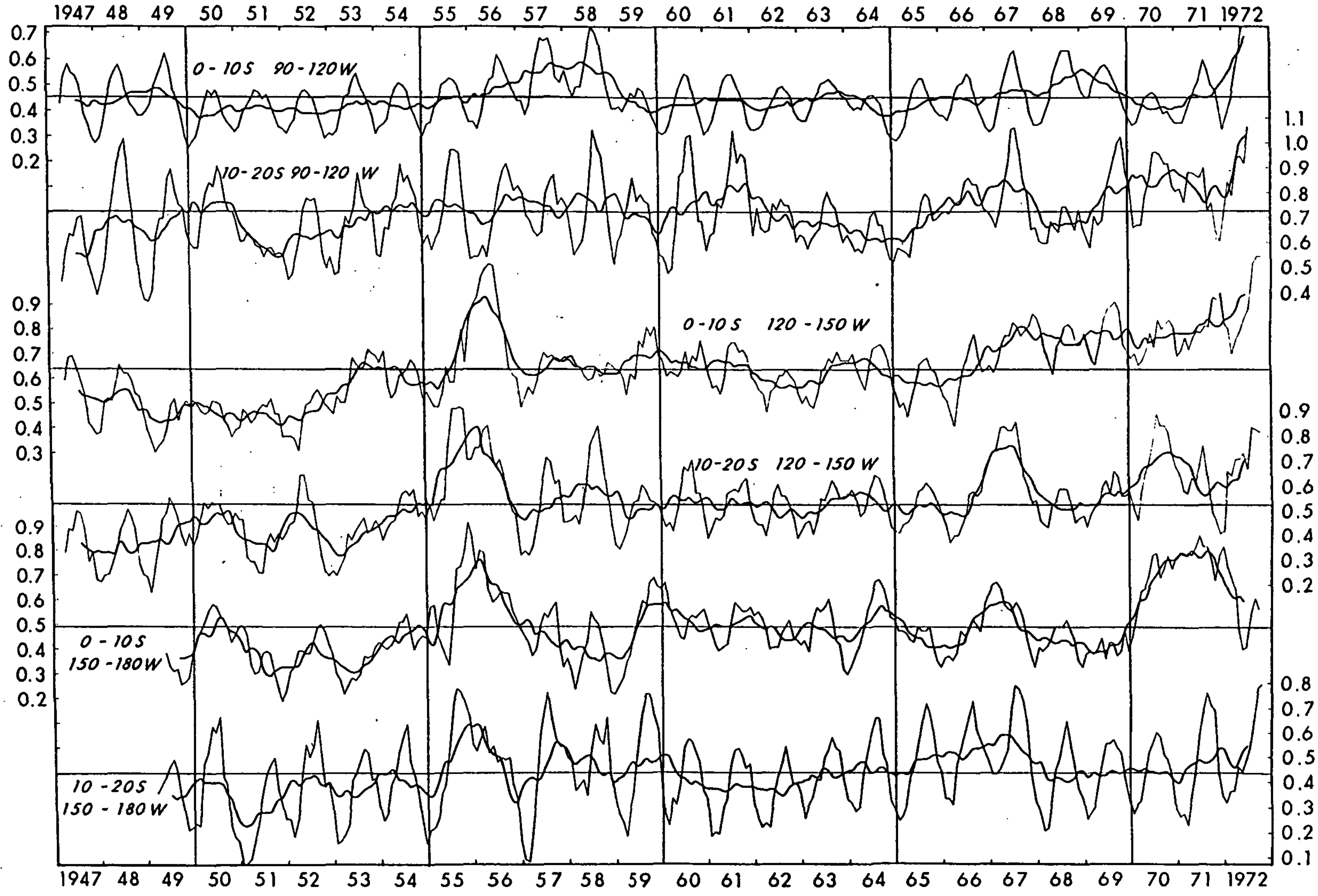

FIG. 5. Zonal component of the wind stress in six sections of the southeast trade wind region from 1947 to 1972 (in 0.1 N m^{-2}, positive to the west). Thin lines give the 5-month running mean, heavy lines the 12-month running mean.

area between 120°W and 180°W and preceded the 1957–58 El Niño. Similarly, abnormally strong winds occurred in 1970 and 1971 over a wide area, preceding the 1972–73 El Niño. The charts of the 700 mb circulation anomaly by Krueger and Winston (1975) also show an abnormally strong development of the southeast trades all the way from South America to the Solomon Islands during the period from March to August 1971. No significant development in the wind field seems to precede the 1965 El Niño, except for the strong equatorial winds between 140°W and 180°W shown in Fig. 4. The peak in wind stress in 1967 between 120°W and 150°W does not seem to have caused an El Niño, although a weak warming occurred in 1969. An inspection of the six curves shows that the wind variations in the area between the equator and 10°S and between 150°W and 180°W correspond best to the occurrence of El Niño. This is in agreement with the previous finding that strong winds along the equator between 140°W and 180°W precede El Niño.

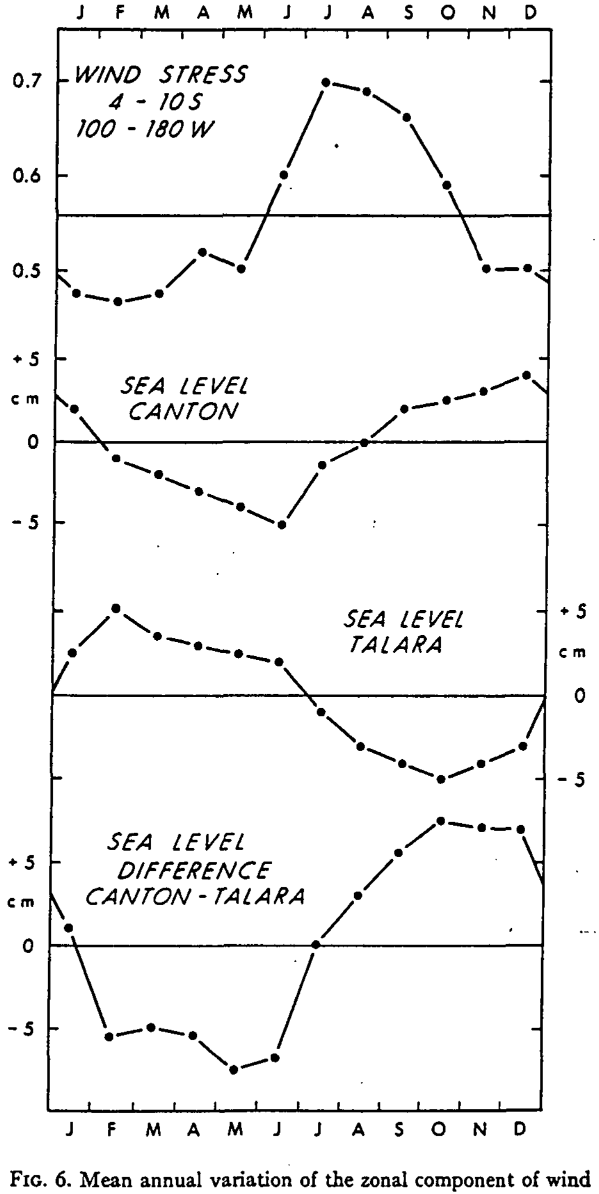

FIG. 6. Mean annual variation of the zonal component of wind stress in the southeast trade wind region (in 0.1 N m^{-2}, positive to the west), of sea level at Canton and Talara (cm), and of the relative sea level difference between Canton and Talara.

7. The slope of sea level under the southeast trades

Sea level at Talara (5°S, 81°W) and at Canton Island (3°S, 172°W) varies approximately out of phase in its mean annual cycle, as shown in Fig. 6; the amplitude is about 5 cm at each station. Related to the dynamic topography relative to 1000 decibars, sea level at Canton Island is about 40 cm higher than at Talara (Wyrtki, 1975). The difference in sea level between Canton and Talara varies by about ±7 cm and, therefore, the slope between the two stations varies from about 33 cm in May to 47 cm in October. This variation is largely in response to the winds as shown in Fig. 6. Strong southeast trades from June to October lead to a progressive increase in the slope. When winds become weaker during southern summer, the slope decreases rapidly and remains small until winds increase again in June. This analysis indicates that the slope of sea level under the southeast trades responds very well to the wind stress in the annual cycle. Consequently, prolonged periods of strong southeast trades will lead to the buildup of a strong east-west slope of sea level under the trade wind belt, and, in particular, to an accumulation of water in the western equatorial Pacific. In the following, this relationship will be used to explain the triggering mechanism for El Niño.

8. A theory for El Niño

In the following I wish to propose a new theory and explanation for the development of El Niño. During a period of strong southeast trades lasting longer than one year, the circulation in the subtropical gyre of the south Pacific is intensified, in particular the South Equatorial Current. This coincides with a buildup of the east-west slope of sea level and an accumulation of water in the western Pacific, most likely in the area between Samoa and the Solomon Islands. As soon as the wind stress of the southeast trades relaxes, the water accumulated in the western Pacific will tend to move back. This may happen in the form of an internal equatorial Kelvin wave (Lighthill, 1969; Godfrey, 1975). In any case, it must happen in a mode consistent with the hydrodynamics of the system. It can be assumed that eastward flow in those currents which normally transport water to the east, the South Equatorial Countercurrent, the North Equatorial Countercurrent, and the Equatorial Undercurrent, will be intensified. The result will be an accumulation of warm water in the area off Peru and, in particular, a depression of the thermocline structure; in essence, El Niño. Consequently, El Niño is a result of the reaction of the Equatorial Pacific Ocean to the relaxation of the southeast trades after a prolonged period of excessively strong winds and the concomitant accumulation of water.

It is now appropriate to discuss the various aspects of this theory in more detail. It has been demonstrated in Sections 5 and 6 that El Niño is preceded by abnormally strong southeast trades, in the central Pacific Ocean, as in 1955–56 and in 1970–71 (Fig. 5). Wind stress was about 50% larger than the long-term mean. Quinn (1974) has used the southern oscillation, namely the atmospheric pressure difference between the Easter Islands and Darwin, Australia, as a predictive index for El Niño. He demonstrates that El Niño will occur after this pressure difference has been high (greater than 13 mb) for an appreciable period. A closer inspection of the Easter Island-Darwin pressure difference reveals that such a peak in the index is due to the failure of the southeast trades to decrease during one particular southern summer. This results in a continuous period of about 18 months, two winters and one intervening summer, of strong southeast trades and a strong pressure difference.

The strong southeast trades will intensify circulation in the subtropical gyre of the South Pacific and will, in particular, strengthen the South Equatorial Current. This intensification of the South Equatorial Current is clearly shown in the time series of equatorial currents derived from sea level differences by Wyrtki (1974, Fig. 3). The South Equatorial Current was abnormally strong in 1955, in 1964, and again in 1970. This should be sufficient evidence that the strong southeast trades during those years caused a strong South Equatorial Current. The strong southeast trades will also lead to a buildup of water in the western Pacific Ocean, in particular, in the region from Samoa to the Solomon Islands. There are unfortunately only a few sea level stations in this area. The records of Pago Pago and Apia (Fig. 7), although interrupted in 1956, clearly show increased sea level from 1954 to 1956 and in 1970–71 coinciding with the strong southeast trade winds and preceding El Niño. A short record from Rabaul also shows a dramatic rise of sea level by 20 cm from July 1970 to March 1971, preceding the 1972 El Niño. Only recently have we been able to install new sea level gauges at Rabaul and on Guadalcanal.

As soon as the stress of the southeast trades relaxes, the strong east-west slope of sea level can no longer be sustained and the water accumulated in the western Pacific must flow back to the east. Such a movement will likely occur in the form of an internal seiche or an internal equatorial Kelvin wave such as discussed by Lighthill (1969) and Godfrey (1975). Besides such wave phenomena, the quasi-steady surface currents are also likely to transport water to the east. The reduced wind

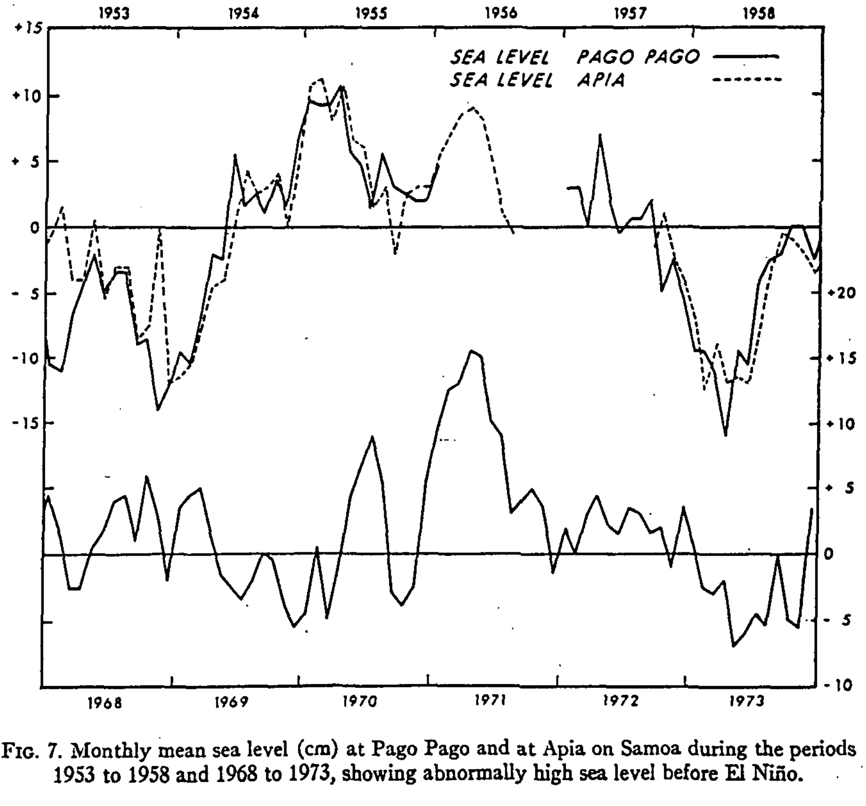

Fig. 7. Monthly mean sea level (cm) at Pago Pago and at Apia on Samoa during the periods 1953 to 1958 and 1968 to 1973, showing abnormally high sea level before El Niño.

stress of the trades will result in a slowdown of the South Equatorial Current, which will allow the South Equatorial Countercurrent to increase in strength. The Equatorial Undercurrent will probably also intensify. That the North Equatorial Countercurrent flows considerably stronger during El Niño has already been demonstrated by Wyrtki (1973), but the Countercurrent reaches maximum strength only in the second half of an El Niño year and might possibly contribute to the second peak in surface temperatures off Peru, as mentioned in Section 3.

Some quantitative assessment of the situation might be appropriate. If sea level in the western Pacific is 10 cm higher, it must be hydrostatically balanced by a thicker upper layer. If the density difference between the warm upper layer and the cold lower layer is $\Delta\rho/\rho=4\times10^{-3}$, then a change of sea level of $\Delta h=10$ cm will imply a change of the thickness of the upper layer by $\Delta H=(\rho/\Delta\rho)\Delta h$ or 25 m. If the thermocline is depressed by this amount over an area of about 2000 by 4000 km from Samoa to the Solomon Islands, the volume of the upper layer will be increased by 200×10^{12} m^3. If this volume of water is to leave the western Pacific during a period of about four months (10^7 s), a horizontal flow of 20×10^6 m^3 s^{-1} is required. This flow is of the same order of magnitude as that of the normal ocean currents in this region.

The water flowing into the area off Peru will accumulate there and will cause a depression of the thermocline which will be demonstrated in the next section. The "back-sloshing" can explain the disappearance of cool water along the coast, but it cannot directly explain the abnormally high temperatures offshore. Since the South Equatorial Current will be slowed down, cool advection is reduced, the residence time of the water in the offshore region will be longer and, exposed to solar radiation, its temperature will increase.

In fact, some theoretical studies which are applicable to El Niño have already been undertaken. White and McCreary (1974) discuss the spindown of a subtropical gyre and find that it involves a weakening of the circulation in the eastern equatorial corner of the gyre. Their approach is basically applicable to the theory presented here, where slowdown of the circulation from a very intense state to a more relaxed state is considered. The main objection to their approach is that they fix the depths of the upper layer at a constant value along the periphery of their model, which forbids the development of waves having a maximum amplitude along the boundary. A much more applicable theoretical study of ocean spindown has been made by Godfrey (1975) using a completely free upper layer. He investigates the movements of a pool of warm water in a decelerating subtropical gyre. Unfortunately, his model ocean is only 22° of longitude long but 40° of latitude wide and consequently does not represent the South Pacific Ocean properly. He describes an internal Kelvin wave progressing east along the equator and shows southward flow along the eastern boundary, both in agreement with the explanation of El Niño presented here. He computes the eastward speed of the non-dispersive Kelvin waves as 2 m s^{-1}, which means that the waves need 60 days to travel 10,000 km across the equatorial Pacific Ocean. This time scale appears to be rather reasonable and might explain the sudden occurrence of El Niño.

9. Downwelling off Peru

The water flowing into the region off Peru after the relaxation of strong southeast trades depresses the thermocline. This effect can be most clearly demonstrated by charting the topography of an isothermal surface or of a surface of constant density. The isothermal surface is to be preferred, because many bathythermograph observations can be used rather than only a few hydrographic stations. The 15°C isotherm in the area off Peru is situated within the thermocline, but intersects the sea surface in the upwelling region during winter. At a prevailing salinity of about 35‰, the 15°C isothermal surface parallels closely the surface where σ_t is 26.0 kg m^{-3} and where thermosteric anomaly is 200 cl per ton. The topography of the 15° isotherm is shown for five occasions in Figs. 8 and 9. During southern winter when upwelling is strong, the 15° isotherm intersects the sea surface in the upwelling region as shown in the map for September 1964 (Fig. 8A). Surface temperatures along the coast are less than 15°C everywhere from 5°S to 17°S. The depth of the 15°C isotherm decreases rapidly away from the coast and reaches depths of 60 to 100 m approximately 300 km offshore. Geostrophic flow as inferred from the isotherm topography is northwest everywhere along the coast. This pattern represents the normal winter situation and is in agreement with the maps of the average depths of the permanent thermocline presented by Wyrtki (1964).

During southern summer the situation is not much different, as illustrated by the 15°C topography for February–March, 1967 (Fig. 8B) observed during the EASTROPAC expedition (Love, 1972). Surface temperatures along the coast are now warmer than 15°C but the warm layer is very thin (20–40 m). The depth of the 15° isotherm decreases less rapidly to about 80 to 100 m at a distance of about 300 km from the coast, indicating that flow is to the northwest also in summer and that upwelling is still present. The only major difference is the depression of the 15° isotherm off Ecuador to over 60 m, which is indicative of southward flow along the coast to about 6°S. Such a depression of the thermocline is also indicated in the mean maps of thermocline topography for March, April and May (Wyrtki, 1964) and must be considered as an annual occurrence. Thus, the patterns in Fig. 8 are typical for normal or non-El Niño conditions.

During 1972 the Instituto del Mar in Peru made three

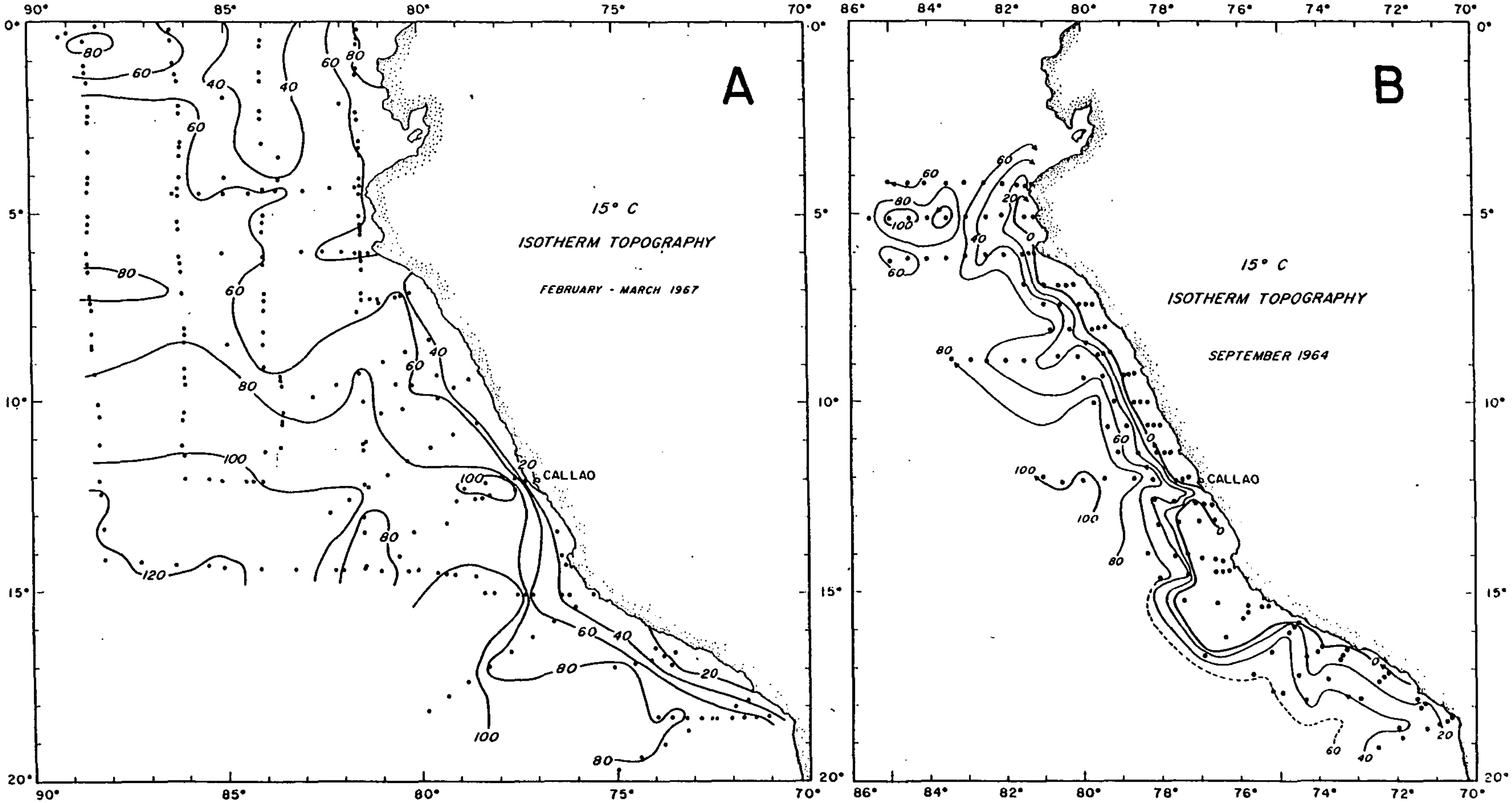

FIG. 8. Topography of the 15°C isothermal surface (m) in the waters off Peru in February–March 1967 and in September 1964, showing conditions during years without El Niño.

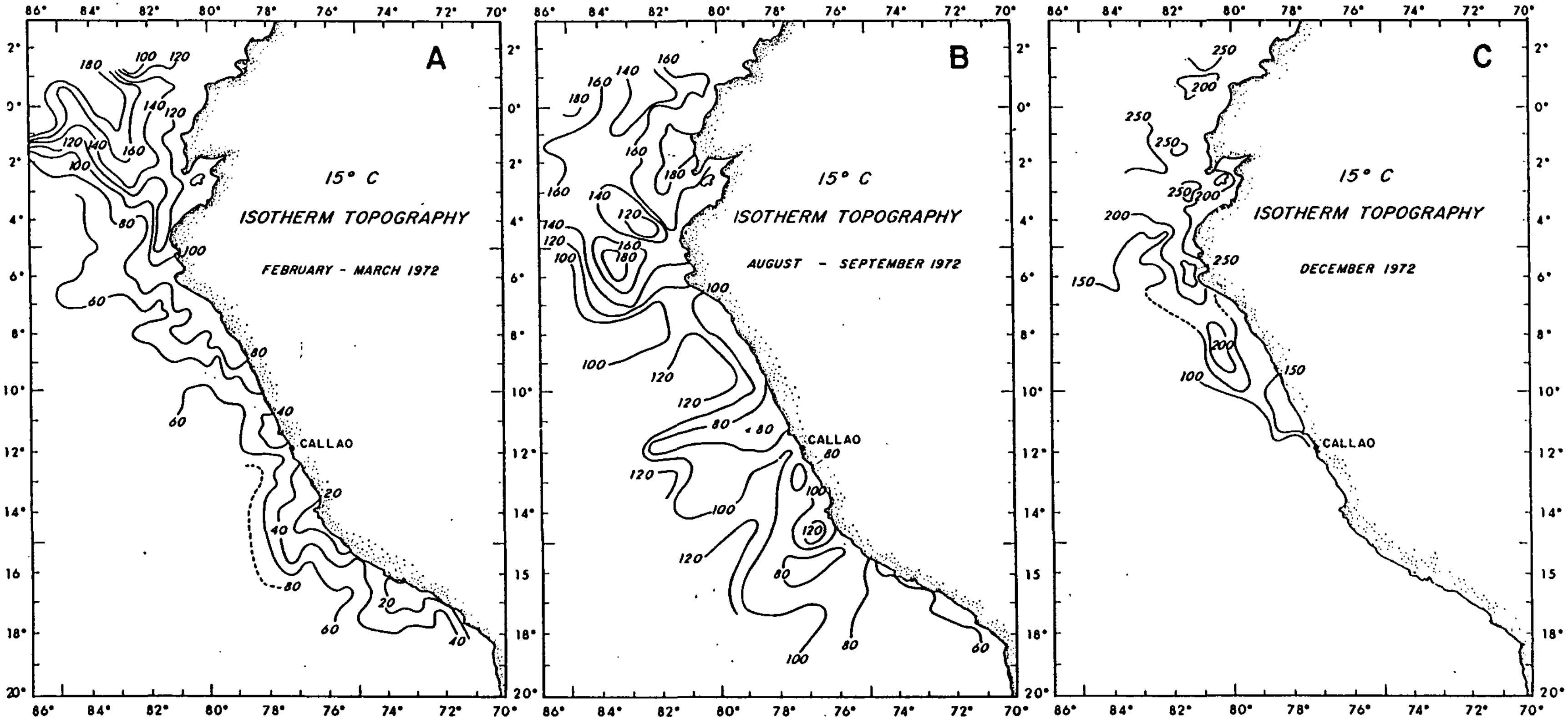

FIG. 9. Topography of the 15°C isotherm (m) in the waters off Peru in February–March 1972, August–September 1972, and December 1972 during El Niño.

cruises into the waters off Peru to observe oceanographic conditions during an El Niño. The topographies of the 15° isotherm for these three cruises have been redrawn from their cruise reports (Zuta *et al.*, 1973, 1974) and are shown in Fig. 9. They are strikingly different from those during normal years. They also allow us to gain some insight into the development of the thermal structure with time during El Niño. In February–March 1972 (Fig. 9A) conditions are about normal south of 10°S, where weak upwelling is apparently still present. Off the coast of Ecuador and Northern Peru, the thermocline has deepened considerably to more than 160 m; it is deepest along the coast and its topography indicates southward flow. Offshore the depth of the 15°C isotherm is still around 60 m. This pattern is in strong contrast to that observed in 1967 (Fig. 8A). It represents conditions at the onset of El Niño and indicates an accumulation of warm water in the surface layer near the equator, off Ecuador and along the coast of northern Peru.

By August 1972 (Fig. 9B) the deepening of the thermocline has become more pronounced and extends along the entire coastline of Peru. The 15°C isotherm is near 80 to 100 m depth off Peru, whereas in normal years, as 1964, it intersects the sea surface and indicates strong upwelling (Fig. 8A). Off Ecuador the 15°C isotherm is now between 140 and 180 m depth, not much deeper than in February, but the area with a depressed thermocline has increased considerably. This indicates that the warm water in the surface layer has penetrated farther southeast along the coast and occupies a larger area and volume.

By December 1972, about one year after the start of El Niño, the thermocline has farther deepened off Ecuador and Peru with maximum depths now reaching 250 m. Unfortunately, the survey was restricted to the area north of Callao and no information is available south of it. The deepening of the thermocline is, however, not restricted to the area off Ecuador and Peru, but extends south along the coast of South America. This has been documented in two maps of the 26.4 σ_t surface published by Robles *et al.* (1974). Their map for winter 1972 (June, July, August) shows this surface to be situated between 200 and 300 m depth all along the coast of northern Chile from 19°S to 24°S. It is deepest along the coast and rises to less than 150 m depth about 200 km offshore. In normal years as in the winter of 1967, the 26.4 σ_t surface is between 50 and 100 m along the coast and deepens to 150 to 200 m depth at about 300 km offshore. In spring of 1972 (September, October, November), the 26.4 σ_t surface is still at 150 to 200 m depth along the coast and shoals to less than 150 m in the offshore area. This kind of isopycnial surface shape clearly indicates southward flow along the coast, which is verified by the dynamic topography of 150 over 500 db shown in the same report.

Summarizing, one can state that El Niño not only affects the surface temperature off Peru, but also causes a complete change in the entire temperature and density structure: an accumulation of warm surface water, a depression of the thermocline, which apparently progresses southward along the coast, and a southward flow of surface and subsurface water along the coast. Because of this depression of the isotherms and the accumulation of warm water along the coast it is no longer surprising that the effects of upwelling are not apparent during El Niño. It has been stated earlier that winds along the coast of Peru are not weaker than normal during El Niño and consequently one must assume that upwelling still takes place, but as long as the warm surface layer is so thick, upward movements will no longer bring cool water to the sea surface. This This might explain the apparent lack of upwelling during El Niño.

10. Concluding remarks

El Niño is a rather complex phenomenon. The appearance of warm water off Peru, the torrential rains, the drop in fish catches and the mass mortality of coastal birds are only the end results in a chain of events in the ocean-atmosphere system. These events certainly encompass the entire equatorial Pacific but are probably of global nature. El Niño also appears in varying intensity and, like any other large-scale event in the ocean-atmosphere system, El Niño certainly does not have only a single cause; no two El Niño events are quite alike.

In this paper I have attempted to outline a mechanism which can explain the very strong El Niño events of 1957–58 and 1972–73. The theory explains only the onset of El Niño as a reaction of the ocean to atmospheric forcing and only the first of the two successive temperature peaks. The second peak is probably related to the strong surge of the North Equatorial Countercurrent described by Wyrtki (1973) and it will require much more research to unravel its causes.

The 1965 El Niño event appears to be rather different: the anomalous temperature peak in the second year is missing; the event is not preceded by strong southeast trade winds, except in the central equatorial Pacific; and winds off Peru were normally weak during summer. It also did not have a catastrophic effect on fishery (Idyll, 1973).

There were two other minor El Niño events in 1951 and 1953; neither had the temperature peak in the second year, neither was preceded by strong trades, but both occurred simultaneously with weak winds over almost the entire southeast trade wind region. In direct contrast, the strong trade winds in 1967 did not cause an El Niño—unless one takes the 1969 warming off Peru as a belated reaction.

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