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Predicting and Observing El Niño

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The occasional appearance of excessively warm water off the coast of Peru is referred to as El Niño. It coincides with the Southern Hemispheric summer, the season of weaker trade winds, and the time of reduced upwelling along the coast of Peru. Several times in the past, 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, which depend on fish for food, die in large numbers. The coastal areas of Ecuador and northern Peru suffer under torrential rainfalls. In total, El Niño amounts to a natural catastrophe.

In the last decade the fishery off Peru has been the largest in the world; its main product is fish meal from small anchovies. The economy of Peru is strongly influenced by its fishery, as is the world market of protein for animal feed (*1*), and so a prediction of the occurrence of El Niño would be a valuable guide for long-range economic planning. Moreover, El Niño is a profound natural event; it is a manifestation of changes in the ocean-atmosphere system over the entire equatorial Pacific Ocean and probably beyond (*2*). Consequently, a capability to predict this event would contribute to the understanding of the large changes occurring in our weather and climate.

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Prediction of El Niño

The occurrence of El Niño is linked to the southern oscillation, as shown by Quinn (*3*). The southern oscillation—a term introduced by Walker (*4*)—is loosely defined by Berlage (*5*) as a fluctuation in the intensity of the intertropical general atmospheric and hydrospheric circulation over the Indo-Pacific region, the fluctuation being dominated by an exchange of air between the southeast Pacific subtropical high and the Indonesian equatorial low. The difference in sea level atmospheric pressure between Easter Island, representing the South Pacific subtropical high, and Darwin, Australia, representing the Indonesian equatorial low, is used as an index to represent the southern oscillation, because pressures measured at the two stations usually oscillate in opposition. Quinn found that an unusually large peak in the 12-month running mean values of the atmospheric pressure difference precedes El Niño by about a year. By using the trend of the 12-month running mean values, a lead time of almost 6 months would be available for a prediction of El Niño from this index. This relationship between El Niño and the southern oscillation index also implies that El Niño is preceded by strong trade winds and coincides with a relaxation of the winds.

Investigating fluctuations of the wind field over the equatorial Pacific Ocean, Wyrtki (*6*) found that strong trade winds lasting more than one year over the central equatorial Pacific precede El Niño, and that winds off Peru are not necessarily weaker during El Niño, which refutes the commonly held opinion that El Niño is due to weak local winds. Wyrtki had previously demonstrated (*7*) that the appearance of abnormally warm water off Central America coincides with strong transports of the North Equatorial Countercurrent and that the highest peaks in these two time series also coincide with, but do not precede, El Niño.

On the basis of these observations and findings, Wyrtki (*6*) proposed a theory, explaining the onset of El Niño as the dynamic response of the Pacific Ocean to atmospheric forcing. He argued that 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 "slosh" back. This may happen in the form of an equatorial internal seiche or as an equatorial Kelvin wave. In any case, it must happen in a mode consistent with the hydrodynamics of the system. It can also be assumed that eastward-flowing currents like the South Equatorial Countercurrent, the North Equatorial Countercurrent, and the Equatorial Undercurrent will be intensified and that the westward-flowing South Equatorial Current will be weakened. The result of this "backsloshing" of the Pacific 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, the onset of 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, leading to an accumulation of water off Ecuador and Peru.

The results of these two investigations by Quinn and Wyrtki were presented at the Eastern Pacific Oceanic Conference in October 1974, where Quinn also presented evidence that the southern oscillation index had reached a new peak and that another El Niño might be expected at the beginning of 1975 (*8*). A small working group was formed, which drafted a proposal to organize an oceanographic expedition to observe the phenomenon early in 1975. The decision to proceed with the expedition was to be made in December 1974 in order to have a research ship in the operational area by February 1975. Fortunately, the National Science Foundation was in a position to make funds available for this expedition within an extremely short time.

The southern oscillation index (Fig. 1) had reached a minimum in 1972, coinciding with the 1972–73 El Niño. After September 1972 the index rose steadily, reaching a maximum in September and October 1973. Thereafter it stayed about level until February 1974. In early December 1974 we had access to the pressure data including October 1974, which permitted computation of the 12-month running mean until April 1974, the month that showed the first significant drop in the index. On the basis of the development of Quinn's index, strengthened by Wyrtki's theory, which gave a logical link between the strong southeast trades and the subsequent occurrence of El Niño, the prediction of El Niño for the beginning of 1975 was reconfirmed at a meeting of the principal investigators in La Jolla, California, in December 1974. In addition, it was stated that the coming El Niño would probably be weak and late. This qualification was based on the observation that the index had not quite reached 13 millibars; that the duration of a strong index, and consequently of strong trades, was less than a year; and that never in the recorded past had two El Niño events followed each other within three years.

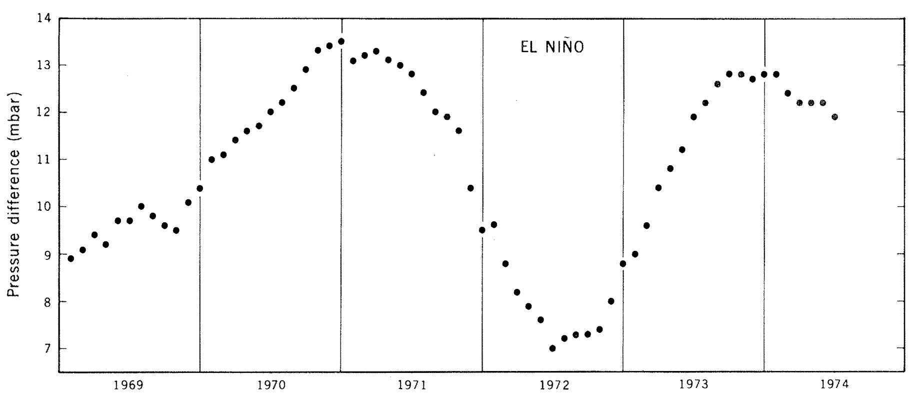


Fig. 1. Southern oscillation index for 1969–74 in relation to the 1972–73 El Niño and the 1975 prediction. The index is given by the 12-month running mean of the difference of atmospheric pressure between the Easter Islands and Darwin, Australia.

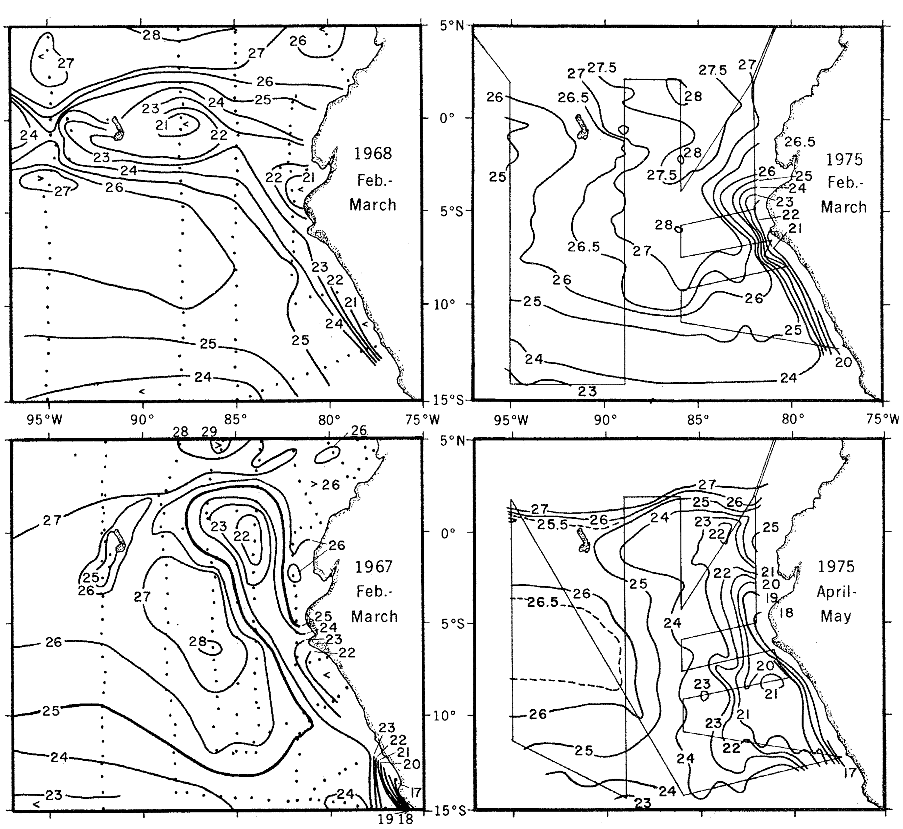


Fig. 2. Sea surface temperature (degrees Celsius) in February to March of 1967 and 1968 compared with that observed during the two El Niño cruises in 1975. Dots show sample locations; in 1975, continuous recordings were made along the ship's track (shown as a thin line).

El Niño Expedition

The oceanographic structure of the area during the season in which El Niño occurs is not unknown; the EASTROPAC (eastern tropical Pacific) expedition observed it twice, in February and March of 1967 and 1968, and the data are analyzed in two excellent atlases (*9*). However, no observations have covered the entire area affected during an occurrence of El Niño. Observations in 1972 were restricted to a narrow coastal strip. In 1967 oceanographic conditions were approximately normal, while in 1968 they were characterized by strong upwelling. It is not generally known where the warm water comes from or whether it is advected or locally produced. Several routes have been suggested: from the north along the coast, from the north in a broad front between the Galápagos Islands and the coast, from the west by a surfacing undercurrent, from the west with a strong South Equatorial Countercurrent, and finally by offshore in situ formation and onshore movements. To investigate all these possibilities, the cruise had to cover the area from north of the equator to west of the Galápagos Islands, as well as the offshore waters and the upwelling region off Peru. Earlier cruises during El Niño had covered only the upwelling area and had therefore not revealed anything about the sources of the warm water. It was also considered necessary to observe the entire area at least twice, to be able to analyze the development of an El Niño with time and to obtain a clear picture about the role of advective processes.

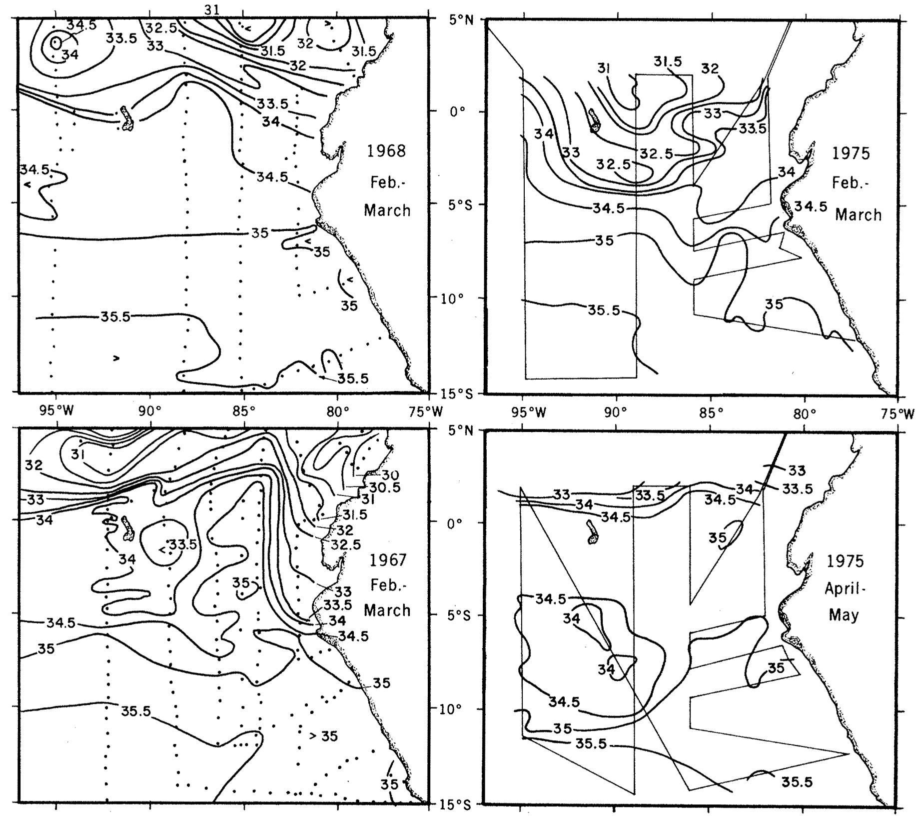
The observational program on board the University of Hawaii's R.V. *Moana Wave* consisted of vertical profiles of temperature and salinity to a depth of 500 meters at stations 60 nautical miles apart, intermediate temperature profiles by expendable bathythermographs at intervals of 20 nautical miles, and hydrographic stations with bottle casts for oxygen and nutrients at intervals of 120 nautical miles. In addition, zooplankton and phytoplankton samples were obtained and primary productivity and chlorophyll were measured. Twice-daily upper air observations with radiosondes and surface meteorological observations at 2-hour intervals constituted the meteorological program on board the ship. The first cruise took place from 11 February to 31 March 1975, the second from 17 April to 27 May 1975; the cruise tracks are shown in Fig. 2.

We will discuss the oceanographic situation observed in 1975 on the basis of three parameters: surface temperature (Fig. 2), surface salinity (Fig. 3), and the depth of the surface where thermosteric anomaly (*10*) is 200 centiliters per ton (Fig. 4). The depth of this surface, which corresponds to the isothermal surface of 15°C at a salinity of 35 per mil, represents the thickness of the upper layer and is an indicator of the topography of the thermocline. These three parameters are chosen because we wish to show the existence of a trans-equatorial flow of warm surface water of low salinity and the deepening of the upper layer along the equator and along the coast of South America, which is characteristic of El Niño conditions (*6*). We will also compare the situation observed in 1975 with that observed during the same month in 1967 and 1968 by the EASTROPAC expedition (*9*), from which the corresponding distributions in Figs. 2 to 4 were redrawn, and describe the development of the 1975 event with time on the basis of the two El Niño cruises.

Oceanographic Situation in the Study Area

The distribution of surface water masses in the study region during normal years is characterized by cool water in the upwelling region off Peru; warm, low salinity water north of the equator; and a pool of warm water to the south and southeast of the Galápagos Islands and offshore from the upwelling region. In 1968 upwelling was strong even in February and March, and the upwelled water was advected northwest past the Galápagos Islands, where surface temperatures were also lowered by equatorial upwelling. The warm water with salinity less than 33.5 per mil remained entirely to the north of the equator in 1968 and was separated from the waters south of the equator by the Galápagos Front (*11*). The warm pool of relatively high salinity water situated southeast of the Galápagos Islands was connected with equally warm water farther west. In general, the situation in February to March 1968 was not unlike that during the peak of the upwelling season from June to September of each year.

In February to March 1967 the cool advection from the upwelling region was less strongly developed and did not reach the Galápagos Islands. No equatorial upwelling was noticeable to the west of the Islands. The warm pool southeast of the Islands was well developed. Warm, low salinity surface water penetrated southward along the coast of Ecuador to about 6°S.



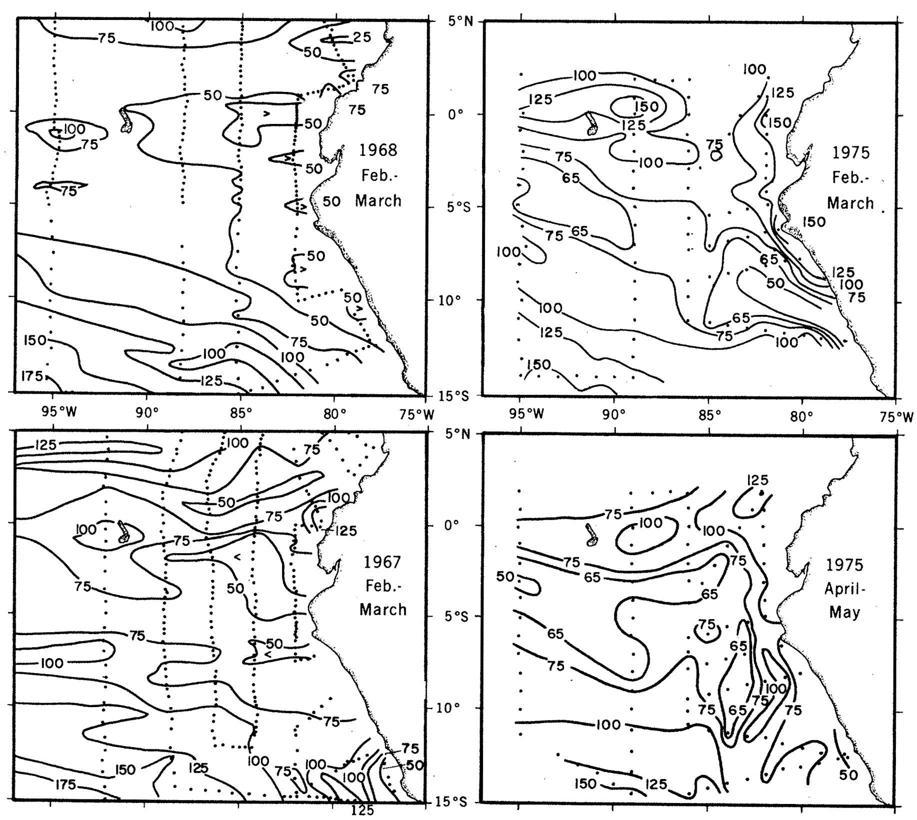


Fig. 3 (top). Surface salinity (per mil) in February to March of 1967 and 1968 compared with that observed during the two El Niño cruises in 1975. Fig. 4 (bottom). Topography of the surface (meters) where thermosteric anomaly is 200 centiliters per ton in February to March of 1967 and 1968 compared with that observed during the two El Niño cruises in 1975. Dots show station locations.

East of the Galápagos Islands a patch of water of salinity less than 34 per mil penetrated south, but the bulk of the low salinity water remained north of the equator.

In February to March 1975 the oceanographic situation was entirely different. Although coastal upwelling was still present, no plume of cool advection extended from the upwelling area to the northwest. East of the Galápagos Islands to 4°S there was a massive advection of water warmer than 27°C and of salinity less than 33 per mil. The Galápagos Front shifted almost 500 km to the south. Vertical profiles of temperature and salinity show that the overflowing layer was only 10 to 25 m thick.

The topography of the 200-cl/ton surface (Fig. 4) is indicative of the thickness of the surface layer as well as of the circulation. The normal situation in a non–El Niño year like 1968 is for this surface to be shallowest along the coast and to become progressively deeper to the southwest, in accordance with the anticyclonic circulation in the subtropical gyre. Between the Galápagos Islands and the coast the 200-cl/ton surface was only about 50 m deep in 1968, indicating that the anticyclonic circulation governed the entire area south of the equator. In 1967 the situation was somewhat different. Along the equator the 200-cl/ton surface was depressed to more than 75 m, which indicated the presence of a rather strong equatorial undercurrent, flowing east. At about 5°S a ridge had developed, where the 200-cl/ton surface rose to less than 75 m and to less than 50 m near the coast. This ridge formed the northern edge of a consistent anticyclonic circulation, and its existence demonstrated that this circulation did not penetrate to the equator in 1967.

In 1975 the situation was similar, but more pronounced. The ridge was very shallow and stretched from about 3°S at 95°W to about 11°S at the coast, limiting the anticyclonic circulation to the area south of it. Along the equator, the 200-cl/ton surface was depressed to more than 125 m, indicating a very strong eastward flow of the undercurrent. But most notable, along the coast of Ecuador and northern Peru the 200-cl/ton surface was also depressed to more than 125 m and in places even to 150 m. This depression indicates not only an accumulation of water carried east by the undercurrent, but also a southward flow of subsurface water along the coast. The depression of isotherms along the coast and the related accumulation of water and its southward flow are characteristic features of El Niño (*6*).

While the observations made during the first cruise in February to March 1975 showed all the features of a starting El Niño, the data from the second cruise showed that it was short-lived. By April and May the temperature in the upwelling region had dropped by more than 3°C and cool water had started to flow toward the Galápagos Islands, as seen by the movements of the 24°C isotherm (Fig. 2). The cool upwelling water had also moved westward, considerably enlarging the area affected by upwelled water. The Galápagos Front had formed again in its normal position near 2°N, as shown by the isohalines (Fig. 3). In this process a patch of warm water with salinity less than 34.5 per mil was cut off and can be seen between 5° and 10°S and 90° and 95°W. This patch is most likely the warm, low salinity water, which crossed the equator during the first cruise and continued to advance southwestward. The topography of the 200-cl/ton surface showed rising motion along the equator and off South America, indicating a weakening of the undercurrent and a strengthening of upwelling along the coast. The topographic ridge present during the first cruise had started to disintegrate, especially close to the upwelling area. In general, the initial development of El Niño did not continue, and oceanic conditions were returning to normal. A comparison of the oceanographic situations during these two cruises demonstrates how significantly this situation can change in a given area in only 2 months.

The year 1975 will not enter oceanographic history as a year of a large El Niño. However, as predicted, an El Niño situation started to develop with a characteristic overflow of warm, low salinity water from the north, an intensification of the undercurrent, and an accumulation of subsurface water along the coast. Without the El Niño expedition these conditions would not have been observed, and from coastal temperatures alone one would have concluded that nothing abnormal had happened. This investigation indicates that only very strong El Niño events have been recorded in the past and that weak occurrences of the phenomenon have remained unnoticed. It is therefore justifiable to reserve the name El Niño for the really spectacular and destructive events lasting a year or more, although there occur similar events of less intensity, which have essentially the same pattern and the same dynamics.

Summary

In October 1974 the occurrence of a weak El Niño event was predicted for early 1975 on the basis of the southern oscillation index. An expedition was organized to observe the event in the waters off Peru and Ecuador during two cruises in order to study its occurrence and its development with time. During the first cruise a massive transgression of warm low salinity water across the equator to 4°S was observed, as well as a depression of the thermocline along the equator and off the coast of South America, indicating the start of El Niño development. During the second cruise the oceanographic situation had changed and conditions were returning to normal.

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12. We thank the National Science Foundation for handling the application for this grant in such an expedient way that the preparation for the two cruises could be conducted in time to observe the El Niño event. We also appreciate the support of the National Science Foundation and the Office of Naval Research as part of the North Pacific Experiment (NORPAX) of the International Decade of Ocean Exploration. We appreciate very much the contribution of the captain and the crew of the R.V. *Moana Wave* and of all members of the scientific party to the success of the expedition, in particular the efforts of the crew in repairing first a damaged rudder and later one of the main engines. Hawaii Institute of Geophysics contribution number 731.