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Oceanographic Events During El Niño

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In July 1982 conditions in the eastern equatorial Pacific were unremarkable; by October the sea-surface temperature (SST) was almost 5°C above normal and sea level at the Galápagos Islands had risen by 22 cm (*1*). The anomalies at depth were even greater: a huge influx of warm water had increased the heat content of the upper ocean at a rate that exceeded the climatological surface heat flux by a factor of more than 3, and the thickness of the warm layer was now greater than all previously observed values (*2*). Temperatures at the South American coast were near normal, but within a month they too would rise sharply. It was now obvious that what had been labeled a warm event would turn out to be a major El Niño, and an exceedingly odd one at that.

In January of a typical year a southward-flowing current brings warm waters to the normally cold coast of Ecuador and Peru. The local fishermen named this current El Niño, in part because of its proximity to Christmas and in part to acknowledge its benevolence: it often carries exotic flora and fauna from its equatorial origins.

At irregular intervals a catastrophic version of El Niño occurs. Massive warming leads to widespread mortality of fish and guano birds, crippling the local economy (*3*). Scientists now reserve the term El Niño for these dramatic events (*4*). Although historical usage prompts a definition of El Niño in terms of conditions off the South American coast, these changes are connected directly to changes across the entire tropical Pacific and indirectly to changes throughout the world's atmosphere and oceans.

Summary. El Niño events, the most spectacular instances of interannual variability in the ocean, have profound consequences for climate and the ocean ecosystem. The 1982–1983 El Niño is perhaps the strongest in this century. El Niño events usually have followed a predictable pattern, but the recent event differs markedly. The physical oceanography of this El Niño is described and compared with that of earlier events.

El Niño events have been documented as far back as 1726 (*5*). On average they occur about once every 4 years, but the interval between successive events has been as short as 2 years and as long as 10 (*5*). There are enough similarities among the different events to justify a common name, and a conceptually useful picture of the typical El Niño has emerged. Nevertheless, no two events are precisely alike with regard to amplitude, time of onset, spatial characteristics, or biological consequences, and aficionados have been known to compare different events in a manner reminiscent of oenologists discussing vintage years.

It is already clear that the 1982–1983 El Niño will be held in special regard. Not only was the amplitude of its thermal signal enormous, but the sequence of the warming and the time of onset deviated markedly from the usual pattern. Thanks to the efforts of many scientists, particularly those in the EPOCS and PEQUOD programs (*6*), this event is the most thoroughly documented one to date.

Interest in the El Niño phenomenon has intensified with the recognition that it is part of a global pattern of anomalies in both the atmosphere and the ocean (*7*). Aspects of the atmospheric changes, notably the Southern Oscillation, were identified before the turn of the century, but an appreciation of their relation to the oceanic El Niño has come only in the past 20 years (*8*). It is now generally felt that the El Niño/Southern Oscillation (ENSO) cycle involves an essential coupling between the atmosphere and the ocean, in which wind changes cause oceanic changes and changes in tropical SST affect atmospheric circulation (*9*). This article addresses the oceanic part of the cycle.

To show how extraordinary the 1982–1983 El Niño was, we will first describe the more typical El Niño and the normal oceanic variations. We will then briefly consider the theoretical explanations that have been offered before discussing the 1982–1983 event.

The Annual Cycle in the Tropical Pacific

Sea-surface temperature along the equator in the Pacific is warm in the west and cold in the east (Fig. 1A). This surface picture also reflects the distribution of oceanic heat content. Almost everywhere in the ocean the surface waters are well mixed by wind stirring. Along the equator in the Pacific this surface mixed layer is usually 150 m deep or deeper in the west, but it becomes shallower to the east until it essentially disappears near the South American coast. Sea level is also higher in the west. The trade winds, driving currents westward along the equator, feed and maintain the buildup of excess warm water on the western side.

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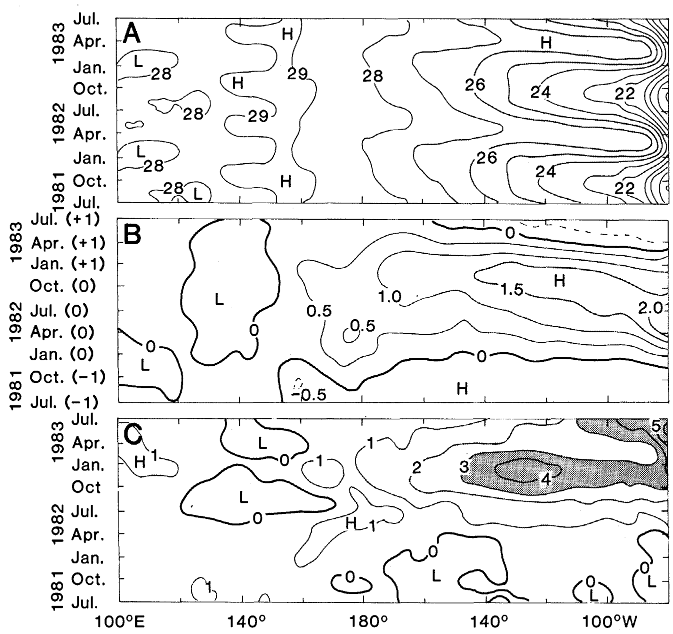


Fig. 1. Time-longitude section of SST. The section follows the equator to 95°W, then follows the climatological cold axis to its intersection with the South American coast at 8°S (*15*). (A) Mean climatology (*4*). The interval from 24° to 27°C is shaded to show the annual warm tongue. (B) Composite El Niño anomalies (*15*). El Niño year is year 0. (C) Anomalies from 1981 to 1983. Note the larger contour interval.

pagos is during the winter and early spring, when the warming occurs (*11*). A number of studies indicate that these changes are the ocean's response to the weakening of the easterly winds along the equator in fall and winter, especially the winds in the western and central Pacific (*12*). An additional component of this response is a deepening of the thermocline, especially along the equator and the coast, so that water upwelled to the surface is warmer than before.

Figure 1A shows that there is very little annual variation in the region west of the date line, which is the largest pool of very warm water in the world ocean. Most of the variability in the tropical Pacific occurs between the South American coast and 140°W from about 3°N to 15°S. This region is also far colder than the mean for the tropics. Most of the flow into it is relatively cold water brought in from the south by the Peru Current. The major outflow is in the west through the South Equatorial Current, which is driven westward by the prevailing trade winds. Water flowing through this region is strongly heated by the atmosphere (*10*), increasing its temperature by several degrees before it reaches the western Pacific.

Coastal and equatorial upwelling are other sources for the cold SST in this region. Winds along the South American coast are southerly, and the Coriolis effect turns the surface currents offshore. The waters leaving the coast are replaced by water from below. Similarly, easterlies induce equatorial upwelling because the Coriolis effect turns the waters poleward in both hemispheres, making the surface flow divergent at the equator. The upward motions associated with both forms of upwelling bring the thermocline, which in the tropics is just beneath the mixed layer, nearer to the surface. Turbulence in the surface mixed layer tends to entrain water from below, mixing it rapidly enough to keep the temperature in the mixed layer uniform with depth. The tropical thermocline is particularly sharp, with temperature changes as great as 10°C occurring in less than 50 m. Hence, differences in thermocline depth can result in drastic differences in the temperature of the water entrained into the surface mixed layer.

Beginning late in the boreal fall there is an annual warming in the usually cold eastern equatorial Pacific (Fig. 1A). In extratropical latitudes the annual cycle of SST variation is primarily a local thermodynamic response to seasonally changing solar heating: temperatures rise through spring and summer, reaching a maximum in fall as the sun retreats equatorward and the net heat balance at the ocean surface becomes negative. This is not the case for the tropical Pacific SST cycle. The eastern tropical Pacific is heated throughout the year (*10*), and the temperature variations are primarily a consequence of basin-wide ocean dynamics rather than local thermodynamics. Variations in the surface heat flux are more a response to SST changes than a cause.

No extant calculations allow a quantitative assessment of the possible dynamic influences on SST in the eastern equatorial Pacific, but there is enough information to indicate which mechanisms are significant. The southeast trades relax, causing the flow through the Peru Current and South Equatorial Current to slow down. Since the rate of surface heating does not decrease, the surface waters become warmer. The weakening of the winds also reduces both equatorial and coastal upwelling, diminishing that source of cold water.

These local factors are aided by remote influences. The waters to the west are always warm, and eastward advection would lead to warming in the east. It is notable that, during a normal year, the only time when there is strong eastward flow along the equator east of the Galápagos is during the winter and early spring, when the warming occurs (*11*).

The Canonical El Niño

Unlike the Atlantic and Indian oceans, the magnitude of interannual variability in the tropical Pacific is as large as the annual signal. In many respects this variability is bimodal in character, taking on one form in El Niño years and another during non–El Niño years (Fig. 2A) (*13*).

All El Niños are different, but recently a composite picture of the canonical event has emerged (*14, 15*). This composite is based on the fact that many aspects of El Niño are closely linked to the annual cycle (Fig. 1, A and B, and Fig. 2). It summarizes our understanding of El Niño before the 1982–1983 event.

Prelude. There are stronger than average easterlies in the western equatorial Pacific for at least 18 months before a strong El Niño event. These winds tend to move water from the eastern Pacific to the west, and consequently sea level is unusually high in the west and low in the east. At the same time the thermocline in the west is deeper than average. SST is slightly warmer than average in the far west and somewhat colder east of 160°E.

Onset. In the fall of the year preceding an El Niño there is already a warm SST anomaly extending across the South Pacific between 15°S and 30°S, with a northward extension across the equator in the vicinity of the date line. In September or October the easterlies begin to diminish along the equator west of the date line. In response the sea level slope along the equator begins to relax.

Event. Warming off the coast of South America begins in December or January, building in magnitude from January to June (Figs. 1 and 3). For the first several months it is difficult to distinguish between an El Niño and normal seasonal warming. The anomaly peaks in April, May, or June. At the same time sea level rises in a narrow region along the South American coast and the thermocline becomes deeper. There is also evidence for a sea level rise along the coast at least as far north as San Diego (*16*). There is strong southward flow at the coast. The SST anomaly at the equator in the vicinity of the date line persists throughout this period (Fig. 1B). At this time there are westerly wind anomalies along the equator from 100°W to 170°E. During the 6 months or so after the peak SST at the coast the warm anomaly spreads northwestward and then westward along the equator until it merges with the anomaly in the central Pacific. Warm water now girdles one-fourth of the globe. By fall, SST at the coast is only slightly above normal, although the colder isotherms are still significantly deeper than normal (*17*).

The westerly wind changes associated with El Niño reduce the strength of the westward South Equatorial Current (*18*). Sea level falls in the west and rises in the east (Fig. 2). In the 1976 El Niño the mass redistribution took place at an average rate of 2.7×10^7 m^3/sec, about half the strength of the South Equatorial Current (*19*).

Mature phase. There is another warming at the coast beginning about December and peaking early in the following year (Fig. 3). This time, however, the coastal SST drops off sharply, perhaps becoming even colder than normal by March. The positive SST anomaly remains in the central and eastern Pacific through the early part of the year (Fig. 1B). It disappears as the colder waters spread westward from the coast, reaching 140°W by about June and the date line late in the year. During this period the winds relax toward their normal pattern and the westward sea level slope is reestablished.

Theory

A complete theory for El Niño must acknowledge that SST changes influence the atmospheric circulation and account for the two-way coupling between the atmosphere and the ocean. The narrower perspective of the oceanographer is adopted here: we seek to understand the ocean's response to prescribed meteorological parameters. Although nonadiabatic processes such as surface heating and wind stirring influence SST changes, we first consider the adiabatic processes that alter the ocean's thermal structure. Many of the observed changes, notably those in coastal sea level, seem largely accounted for by a linear theory based on wind variations (*20, 21*) that emphasizes the special role of the equatorial wave guide.

The ocean's adiabatic response may be analyzed as a sum of free and forced waves. For the time and space scales of importance in El Niño events, only two types of wave motions are of possible importance: Rossby waves and equatorial Kelvin waves. Away from the equator the principal dynamic balance in the ocean is the geostrophic one between Coriolis and pressure gradient forces; this balance is characteristic of Rossby waves and strongly constrains their propagation speeds. The vanishing of the Coriolis parameter at the equator allows another low-frequency wave form, the equatorial Kelvin wave. While the Rossby waves generated by the wind propagate westward, the Kelvin wave carries energy eastward. It is also very fast: the gravest baroclinic (*22*) Kelvin wave can cross the Pacific in less than 3 months. The most equatorially confined Rossby wave is three times slower, and the Rossby wave speed decreases as the square of the latitude, so mid-latitude waves would need decades to cross the Pacific.

The special properties of equatorial motions are essential to the El Niño phenomenon. A given change in the wind generates a stronger response at the equator than elsewhere in the ocean, and equatorial waves are less susceptible to the destructive influences of friction

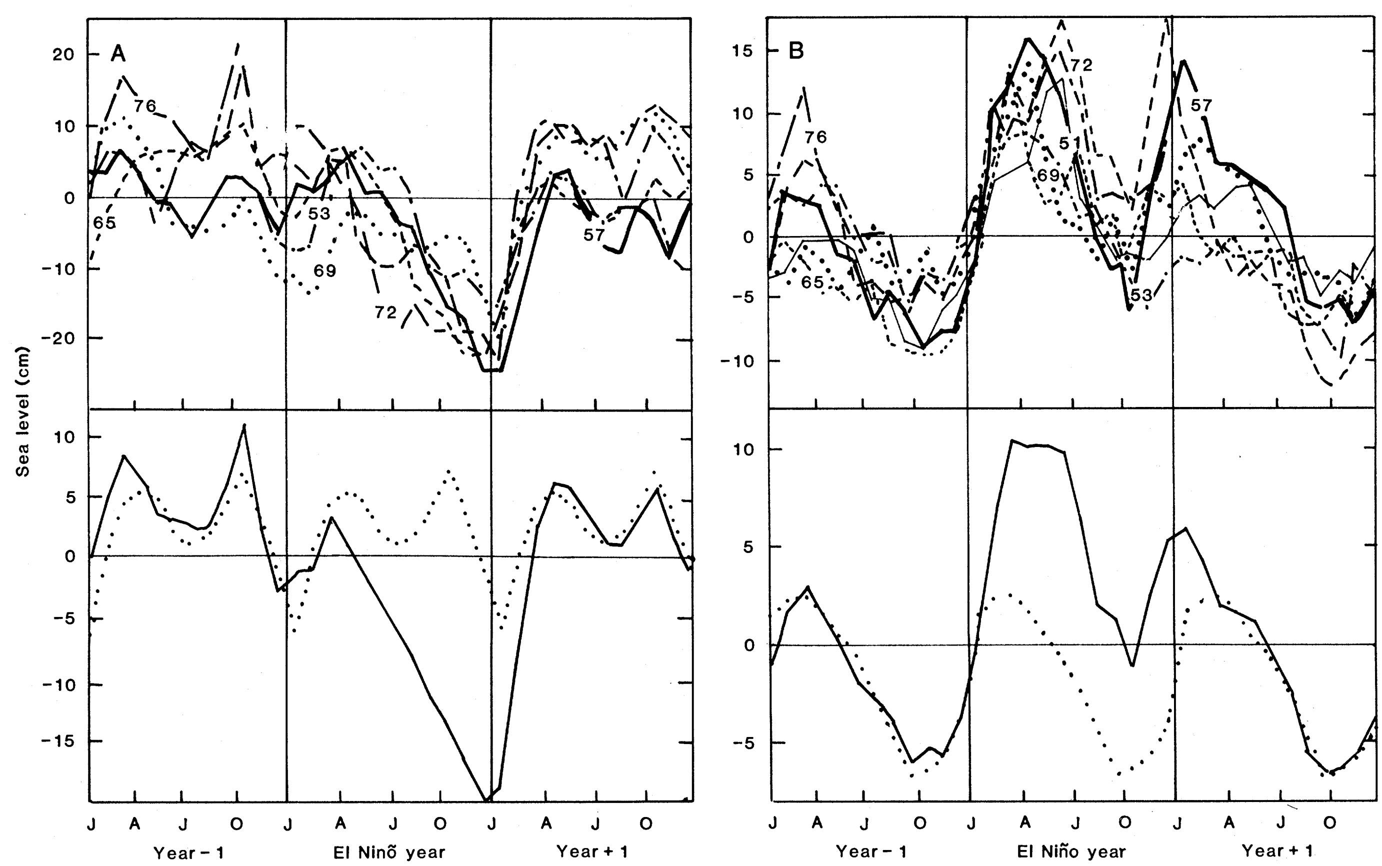


Fig. 2. El Niño signatures. (A) Sea level at Truk (152°E, 7°N) during indicated El Niño events (top panel), for the composite El Niño (bottom panel, continuous line), and for the annual mean in non–El Niño years, 1953 to 1976 (bottom panel, dotted line). Note the similarity among El Niño events and their collective difference from the semiannual cycle of non–El Niño years. (B) Curves as in (A) but for sea level at Callao (79°W, 12°S). In the eastern Pacific, El Niño events typically appear as an enhancement of the annual cycle.

and mean currents. We have noted that the prevailing equatorial easterlies pile up warm water in the west. A relaxation of the winds in the western or central Pacific excites packets of equatorial Kelvin waves. There is strong observational evidence (*23*) that the equatorial wave guide is effective enough to allow such waves to cross the Pacific to the eastern boundary within a few months, raising the sea level there.

In principle, the local setup in response to alongshore winds can also alter the thermal structure at the coast, but in fact there is little change in the coastal winds during El Niño except at very low latitudes (*24*). Hence, changes in the currents and in all aspects of the thermal structure, including sea level displacement and thermocline depth, depend primarily on the amplitude of the incident Kelvin waves.

The amplitude of the incident Kelvin wave is determined by its initial value at the western side of the Pacific plus the amount added by wind forcing as it propagates along the equator. Model calculation (*21*) indicates that the latter is the principal influence. Further, the only forcing that matters is the zonal wind stress within a few hundred kilometers of the equator. Figure 4 shows this forcing for the gravest baroclinic mode as a function of longitude and time (*25*). The dashed lines show the path of a Kelvin wave. It is evident that for the composite El Niño the primary cause of the rise in sea level at the beginning of the El Niño year is the anomalous westerlies west of the date line. The second peak later in the year is due to the more massive collapse of the trades east of the date line.

The foregoing discussion is offered as an explanation of the observed changes in sea level and thermocline depth; it does not account for SST anomalies. Data for the 1972 El Niño show that, averaged over the whole event, surface heating does not contribute to the warming; in fact, because of increased evaporation the net flux anomaly is out of the ocean (*26*). It is, of course, possible that there is a net surface heating part of the time. Leetmaa (*27*) suggested that this may be the case shortly after onset in a region of the eastern Pacific south of the equator (85°W, 5°S), although the heat flux data are very uncertain. His study also indicated that some of the warming results from a slowing of the currents (*28*) through the area while the surface heating rate is undiminished. What Leetmaa demonstrated most forcefully, however, is that the principal cause of the warming is a rise in the temperature of the water flowing into the area studied.

The likely source of this warmer water is the South American coast. The initial warming during an El Niño takes place at the coast. This is true despite the fact that, since the alongshore winds do not weaken, coastal upwelling is unabated. However, after the equatorial Kelvin wave arrives at the coast the thermocline is pushed down, with the result that the water mixed into the surface layer is warmer than before. A second and possibly more important factor is the advection of warm water by the southward-flowing El Niño coastal current. This current is another aspect of the Kelvin wave impinging on the coast. Thus the surface warming is directly related to the adiabatic, remotely wind-driven physics discussed above.

There is both theoretical (*29*) and observational (*1*) evidence that eastern Pacific waters south of the equator never reach the equator. Hence, different waters are involved in the equatorial warming, which at its peak extends some 10,000 km from the South American coast to the date line (Figs. 1 and 3). The winds over this region are anomously westerly [Fig. 4; also see figure 4 of Rasmusson and Wallace (*7*)], so the westward surface currents along the equator weaken, reducing the flow of colder water from the coast. (In a strong event the currents may even reverse, carrying in warmer surface water from the west.) Since the surface heating rate remains high the slower moving waters become hotter than normal. At the same time the flux of cold water from below the surface mixed layer is diminished because the weakening of the local easterlies reduces equatorial upwelling. In addition, the remaining upwelled water is now warmer because remotely and locally generated Kelvin waves act in concert with their subsequent reflections at the coast to depress the thermocline.

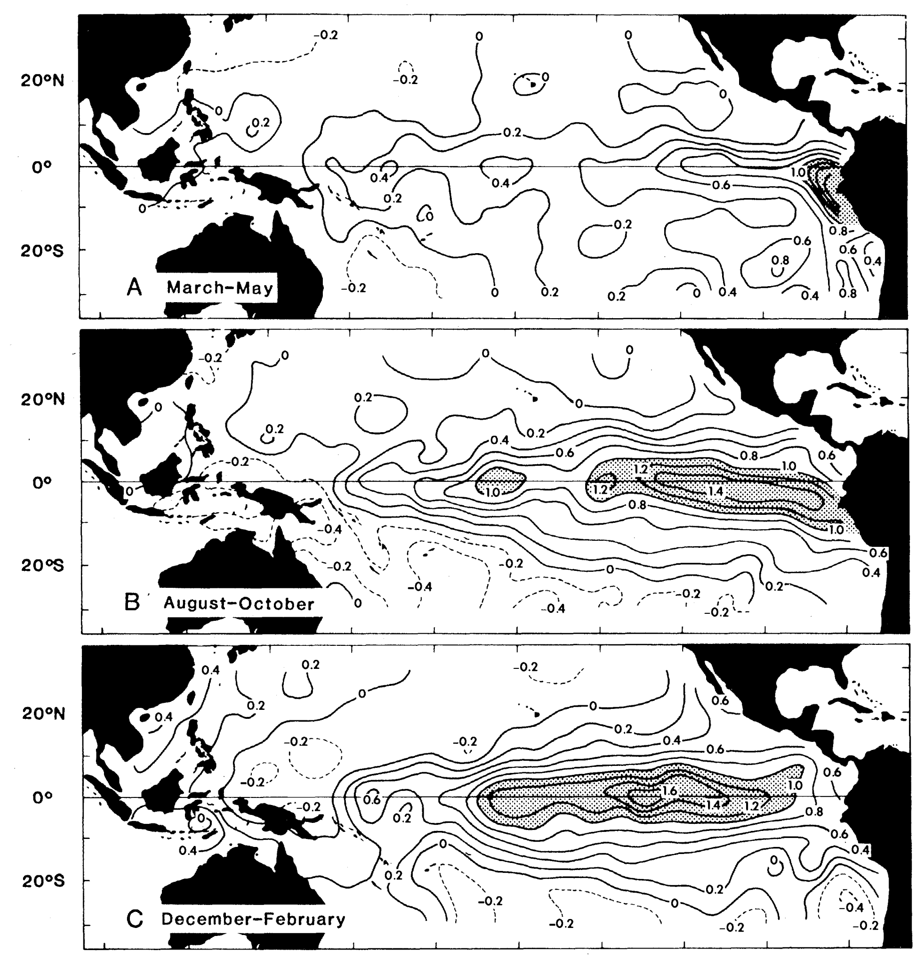


Fig. 3. *Sea-surface temperature anomalies* (°C) for the composite El Niño (*15*). Contour interval is 0.2°C. (A) March, April, and May average during El Niño. (B) Average for the following August through October. (C) Average for the following December through January.

The 1982–1983 El Niño

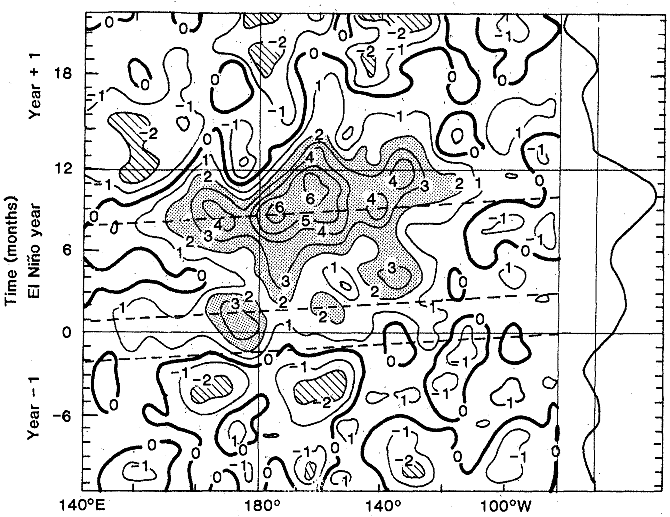
The wind anomalies that presage the typical El Niño occur in fall, but the earliest signs of the 1982–1983 event appeared in spring. There were bursts of westerlies in the vicinity of the date line (*30*), but in view of the great variability of the winds in this area their significance was uncertain. By May there was a noticeable SST anomaly (Fig. 1C). (Its amplitude was small, but SST variability in this area is slight.) By July the wind anomaly was sufficiently strong and persistent to make it clear that something unusual was afoot.

However, none of the usual precursors of an El Niño event were present. The easterlies had not been especially strong and there was no tendency for SST to be unusually low in the east and high in the west. Sea level had not built up in the western Pacific and the thermocline was not unusually deep there (*31*).

In early summer, SST in the eastern Pacific was a bit above the climatological mean but well within the normal range of interannual variability (*32*). By August, warming in this area was substantial (Fig. 1C) and the winds were highly anomalous, with westerlies replacing easterlies over much of the equatorial Pacific. In a reversal of the usual El Niño pattern (*15*), the mid-ocean warming did not lag behind major anomalies at the South American coast (Figs. 3 and 5).

In the early part of the year, sea level in the western Pacific followed its normal course, reaching a peak in March or April and then falling off (*33*). In a typical year it rises again to a second peak in the fall (Fig. 2), but in 1982 it continued to drop throughout the year (Fig. 6). The drop-off was especially sharp at the end of June: sea level fell 12 cm at Rabaul (4°S, 152°E) and 18 cm at Honiara (10°S, 162°E).

In the mid-Pacific (Fanning Island in Fig. 6), sea level was near normal into June and then began to rise rapidly: from June to September sea level at Christmas Island (2°N, 157°W) rose 25 cm; in a normal year it increases gradually until December, with a total change of 10 cm.



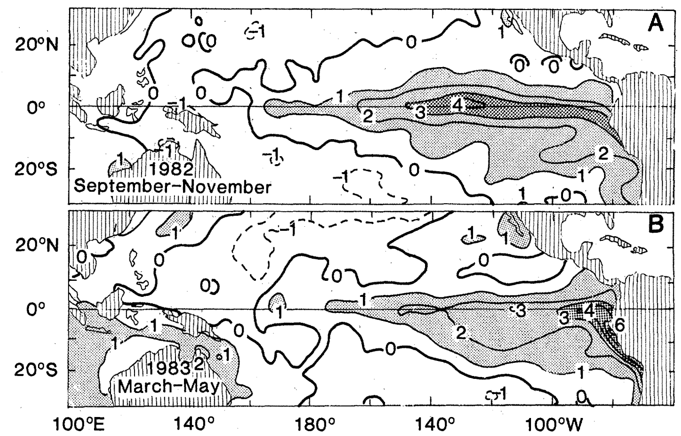
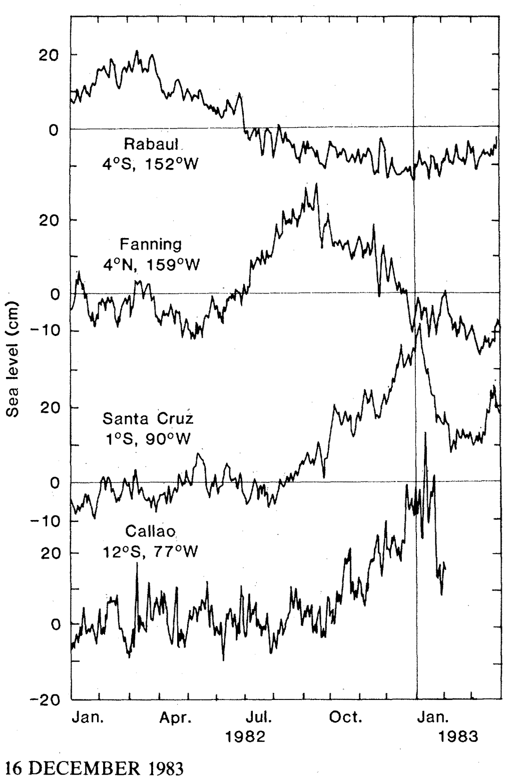


Fig. 4 (left). Forcing for the gravest baroclinic Kelvin wave, based on the composite El Niño wind anomaly field (*21*). Dotted lines indicate the path of a Kelvin wave. The curve on the right gives the Kelvin wave amplitude at the eastern boundary. It is a measure of sea level change (or thermocline displacement) at the South American coast. Fig. 5 (right). Sea-surface temperature anomaly maps for the 1982–1983 event (*41*); compare with Fig. 3. (A) September to November 1982. (B) March to May 1983. Figure 5C in Rasmusson and Wallace (*7*) shows December 1982 to February 1983.



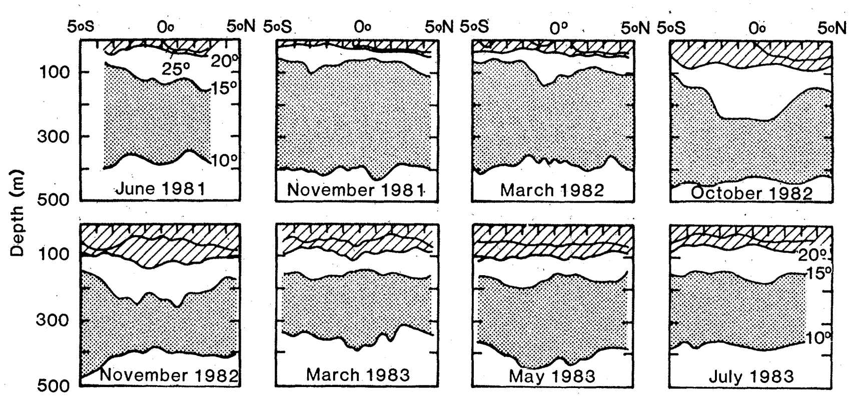


Fig. 6 (left). Sea level time series at selected tropical Pacific stations (*42*). Rabaul is typical of the western Pacific, Fanning of the central Pacific, and Callao of the South American coast. Note that sea level falls in the west and rises in the east. The changes progress eastward with time. Fig. 7 (right). Temperature sections (°C) along 85°W (*43*). Sections for 1981 and March 1982 illustrate normal conditions.

At Santa Cruz, 8000 km to the east in the Galápagos, sea level began its rise in August, while at the coastal stations (for example, Callao, Peru, in Fig. 6), sea level began to rise in late September or October.

Subsurface effects were, if anything, more unusual (Fig. 7). In November and December 1981 the center of the thermocline (the 20°C isotherm) at 85°W on the equator was centered at a depth of 40 m; a year later it was twice as deep (*1*). Similar depressions of the thermocline were observed throughout the eastern half of the Pacific out to 160°W (*34*). From July to October, SST at 0°N, 110°W rose about 2°C while the temperature at a depth of 100 m increased by 8°C (*1*). This huge accumulation of warm water in the eastern Pacific was apparently sufficient to reverse the pressure gradient along the equator (*35*). As a result, the eastward-flowing Equatorial Undercurrent (*36*) began to disappear during August at 159°W and did not reappear until January 1983 (*35*). To our knowledge, this was the first time that direct measurement failed to show an undercurrent in the central Pacific (*37*).

These changes are consistent with the idea that packets of Kelvin waves were excited by the wind changes in the central and western Pacific and propagated eastward along the equator to the South American coast, raising sea level as they went. This scenario was used to account for the canonical El Niño event, but in 1982 the pattern of SST changes was very different, probably because the timing of the event was so different from that of the annual cycle.

We noted above that the equatorial and coastal warmings are distinct. In 1982 the equatorial warming proceeded as usual: surface currents changed from westward to eastward with passage of the Kelvin waves, carrying warmer water into the region; at the same time the suppression of the thermocline meant that waters upwelled along the equator were warmer than before. El Niño events usually coincide with the annual coastal warming, acting in concert with mean conditions to import warmer surface waters and depress the thermocline. The 1982–1983 event reached the coast in late summer, when the temperature is normally headed toward its minimum value. Once the event took hold, however, the results were dramatic: SST at Callao rose 2°C per month through the last third of 1982 (*38*). In 1983 coastal temperatures continued to rise through the normal warming period and beyond, exceeding climatological values by 6°C or more by June.

Discussion

We have emphasized the unusual nature of the 1982–1983 event, but in many respects it followed the typical El Niño pattern. The canonical event begins with a weakening of the easterlies in the fall, at the time of the transition of the Asian monsoon from its summer to its winter form. This leads to a winter warming at the South American coast that then spreads westward. After a turn toward normalcy there is a second peak in the characteristic El Niño signal (Fig. 2) stemming from a more massive collapse of the trades that begins in the spring (the time of the other monsoon transition). The 1982–1983 event began with similar spring changes; the first phase was missed.

This characterization is reinforced by changes reported at the time of this writing (July 1983): temperatures at the coast have started to decrease toward normal and the wind system appears to be returning to its normal pattern (*39*). However, SST in much of the eastern equatorial Pacific remains well above normal, a reminder that this event is one of the strongest ever recorded.

While the 1982–1983 event was unusual, it was not unprecedented. The very weak event of 1963 had some similar characteristics, and there are suggestions that the major events of 1930 and 1941 followed a similar pattern [(*7*); figure 11 of Rasmusson and Carpenter (*15*)]. In any case, analogies to past events are too imperfect and our understanding of the phenomenon is too incomplete to permit confident prediction of the behavior of El Niños like the 1982–1983 event.

The tropical locus of El Niño events may be attributed to equatorial ocean dynamics. However, although the same physics governs all three tropical oceans, El Niño is unique to the Pacific. We suspect this is a consequence of the singular influence of tropical Pacific SST on the atmospheric circulation. The atmospheric circulation is largely powered by the three tropical heat sources located over Africa, South America, and the Australasian maritime continent. The last of these is by far the strongest, and, not being anchored to a landmass, is also the least sedentary, migrating with the changing seasons. It becomes amorphous during the transition periods of the Asian monsoon, and we speculate that it is vulnerable to anomalous influences at these times. We further speculate that SST variations of relatively small amplitudes in the warm western tropical Pacific can induce excursions into the central Pacific of the kind observed to precede El Niño events (*40*). Throughout the event, surface wind changes cause changes in SST in the manner we have described, and these SST anomalies feed back on the atmosphere, inducing further wind changes, until the entire ENSO cycle is played out.

The 1982–1983 event is the best-observed El Niño to date, and analysis of it should prove valuable in developing our understanding of ocean physics and atmosphere-ocean interactions. The maverick nature of this event is an additional virtue: we cannot do controlled experiments, so it is helpful to have nature do one for us. The event has already shown us that the first phase of the typical El Niño is not essential; further study may give us insight into the cause of El Niño and lead to an ability to predict these climatically important events.

Note added in proof: The return toward normal has continued into October, but SST remains high. In the canonical El Niño, SST in the eastern Pacific decreases very rapidly at the end of the event, falling below the climatological value (Fig. 1B).

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44. I thank the many colleagues who reviewed an early version of the manuscript. Special thanks are extended to those who generously contributed unpublished data and to Lenny Martin for assistance in preparing the manuscript. This work was supported by grant OCE-8214771 from the National Science Foundation.

Meteorological Aspects of the El Niño/Southern Oscillation

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Summary. The single most prominent signal in year-to-year climate variability is the Southern Oscillation, which is associated with fluctuations in atmospheric pressure at sea level in the tropics, monsoon rainfall, and wintertime circulation over North America and other parts of the extratropics. Although meteorologists have known about the Southern Oscillation for more than a half-century, its relation to the oceanic El Niño phenomenon was not recognized until the late 1960's, and a theoretical understanding of these relations has begun to emerge only during the past few years. The past 18 months have been characterized by what is probably the most pronounced and certainly the best-documented El Niño/Southern Oscillation episode of the past century. In this review meteorological aspects of the time history of the 1982–1983 episode are described and compared with a composite based on six previous events between 1950 and 1975, and the impact of these new observations on theoretical interpretations of the event is discussed.

Each year various parts of the globe experience regional climate anomalies such as droughts, record cold winters, and unusual numbers of storms. But some years, such as 1982 and 1983, are characterized by large, remarkably coherent climate anomalies over much of the globe. The pattern inherent in these anomalies has been recognized gradually, over a period of decades, as a result of the collection and analysis of many different climatic records; the recognition process has been somewhat like the assembly of a global-scale jigsaw puzzle.

Some of the pieces of this puzzle are implicit in the Southern Oscillation, a coherent pattern of pressure, temperature, and rainfall fluctuations discovered and named by Sir Gilbert Walker more than a half-century ago (*1*). The primary manifestation of the Southern Oscillation is a seesaw in atmospheric pressure at sea level between the southeast Pacific subtropical high and the region of low pressure stretching across the Indian Ocean from Africa to northern Australia. Other manifestations involve surface temperatures throughout the tropics and monsoon rainfall in southern Africa, India, Indonesia, and northern Australia (*2, 3*). When Walker's scientific contemporaries expressed doubts concerning these statistical relations because of the lack of a physically plausible mechanism for linking climate anomalies in far-flung regions of the globe, he replied, "I think the relationships of world weather are so complex that our only chance of explaining them is to accumulate the facts empirically . . . there is a strong presumption that when we have data of the pressure and temperature at 10 and 20 km, we shall find a number of new relations that are of vital importance" (*4*).

Descriptive studies of the 1957–1958 El Niño event, based in part on routine merchant ship data from the tropical Pacific, were instrumental in revealing the link between El Niño and the Southern Oscillation. The large-scale interaction between atmosphere and ocean was confirmed by retrospective statistical studies of past episodes (*5*). The emerging unified view of the El Niño/Southern Oscillation (ENSO) phenomenon is exemplified by Bjerknes's investigations (*6*) of the 1957–1958, 1963–1964, and 1965–1966 ENSO episodes. These studies were among the first in which satellite imagery was used to define the region of anomalously heavy rainfall over the dry zone of the equatorial central and eastern Pacific during episodes of warm sea-surface temperature (SST), an aspect of the phenomenon that Walker apparently was unaware of. Bjerknes showed that these fluctuations in SST and rainfall are associated with large-scale variations in the equatorial trade wind systems, which in turn reflect the major variations of the Southern Oscillation pressure pattern.

The linking of El Niño with the Southern Oscillation was viewed as evidence that ocean circulation plays the role of a flywheel in the climate system and is responsible for the extraordinary persistence of the atmospheric anomalies from month to month and sometimes even

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