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Equatorial Undercurrent Disappears During 1982–1983 El Niño

Abstract. *The equatorial undercurrent at 159°W decayed during August 1982, partially reversed during September, and rapidly reappeared in January 1983. The virtual disappearance is consistent with the basin-wide adjustment of sea surface slope to the strong westerly winds in the western and central Pacific that caused the 1982–1983 El Niño event.*

El Niño events are usually described in terms of sea-surface temperature, sea level, winds, rainfall, and, to a lesser extent, hydrographic structure (*1*). Until the 1982–1983 event there were few measurements of currents near the equator during El Niño. Current measurements made along 159°W from March 1982 through June 1983 (*2*) show that currents, like the winds, reverse during El Niño.

During March through July 1982, currents at the equator (Fig. 1) were marginally weaker than during the same season in 1979 and 1980. The Equatorial Undercurrent (EUC) flowed east with a maximum speed of 1 m/sec at a depth near 150 m. Western flow in the South Equatorial Current (SEC) was weak. The EUC surfaced in April and eastward surface flow remained through most of the boreal summer (*3*).

During August the upper and middle parts of the EUC vanished, and a westward current appeared at the core depth (150 m) during September and October. Below 160 m the EUC was reduced to a small remnant during September. This is the first time, to our knowledge, that direct current measurements in the central Pacific have failed to show a substantial EUC. A meridional section of current profiles during late September confirms that the EUC was really absent rather than shifted off the equator.

During November, eastward flow returned at 150 m due to the deepening of a strong surface current rather than the restoration of a normal EUC. The EUC, with a strong SEC above it, returned abruptly in January. From mid-February through the last observations in June, the maximum speed of the EUC remained over 0.7 m/sec while that of the SEC varied from 0.2 to 1 m/sec.

What caused this disappearance of the undercurrent?

Ship and island wind measurements from 160°E to the date line show westerly anomalies beginning in June, with westerly winds persisting from July through November (Fig. 2). The rapid return of easterly winds at Tarawa in December was accompanied by a strong northerly component and by continued westerlies south of the equator. At 159°W within 3° of the equator, steady easterly trade winds prevailed until September, when they rapidly weakened. Winds were light and variable during October. Starting in November, bursts of strong westerlies were associated with vigorous convection and precipitation in the normally arid equatorial band.

Monthly average sea levels at islands near the equator (Fig. 3) show the basin-wide adjustment of the sea surface during El Niño. In June the sea levels were near their long-term averages, with the normal slope down to the east (*4*). Starting in July, the sea surface began a gradual fall in the far west. At Nauru, Christmas Island, and the Galápagos Islands, sea level rose and then fell at successively later times. By January there was essentially no slope across the basin at the zonal scales resolved by these widely separated islands.

The disappearance of the EUC at 159°W in September coincided with the peak in sea level at Christmas Island (157°W) and with the collapse of the local trade winds. The high sea level is consistent with a reduced or reversed pressure gradient, hence with weak westward flow replacing the EUC core. The

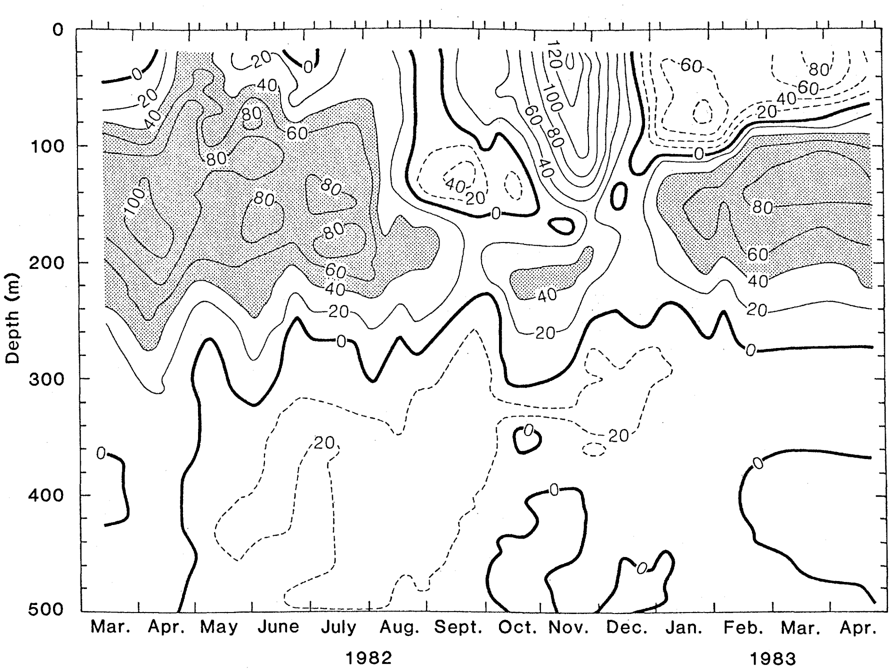

Fig. 1. Zonal velocity component on the equator at 159°W. Contour intervals are 20 cm/sec, with westward flow indicated by dashed lines. Tick marks at top show observation times. The EUC (shaded) was virtually absent from September through December 1982.

rise in sea level before the local wind anomaly is consistent with the hypothesis that internal Kelvin waves generated by westerly winds in the western Pacific altered the zonal sea surface slope (*5*). The fast rise in sea level at Christmas Island was caused by a low baroclinic mode; isotherms measured simultaneously with currents at 159°W descended throughout the upper 500 m. Daily mean sea level records show that the major rise in sea level propagated from Jarvis Island (0.4°S, 160°W) to the Galápagos in about 30 days. The propagation speed, 2.9 m/sec, is reasonable for a first baroclinic mode Kelvin wave. The increase in eastward velocity due to this Kelvin wave is largest in the mixed layer. It caused the EUC to surface and briefly strengthen in July 1983. Higher vertical modes propagate less rapidly and have smaller effects on sea level. However, they can produce the complicated vertical alternation of currents seen during El Niño.

The complex current fluctuations after the September onset of anomalous local winds were probably due to both local and remote forcing. In addition to Kel in waves from the west, Rossby waves from the east can change pressure gradients and currents. Rossby waves can be generated by zonal wind gradients and by the reflection of Kelvin waves at the South American coast.

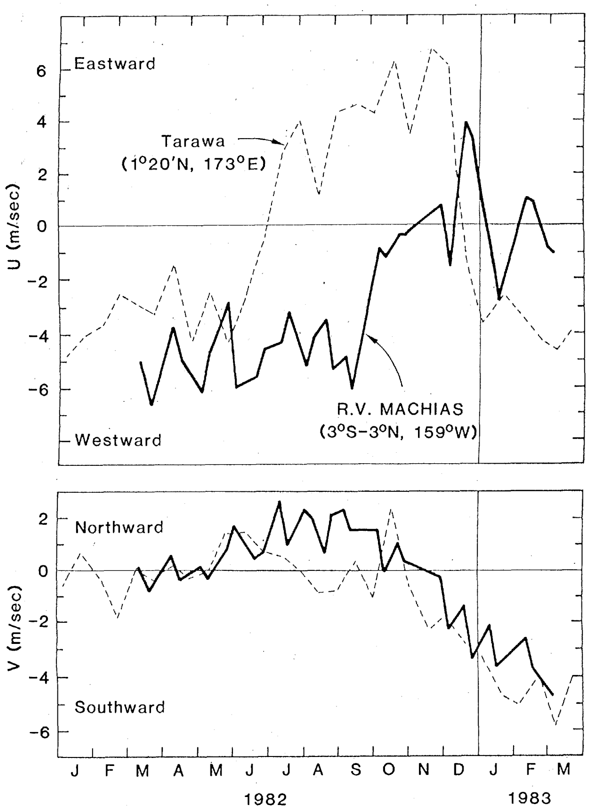

Fig. 2. Zonal (*U*) and meridional (*V*) wind components near the equator in the western Pacific (dashed lines) and central Pacific (continuous lines). Strong westerly wind anomalies began in the western Pacific during June 1982 and gradually extended to the east. The northerly wind anomaly appeared simultaneously in the western and central Pacific early in 1983.

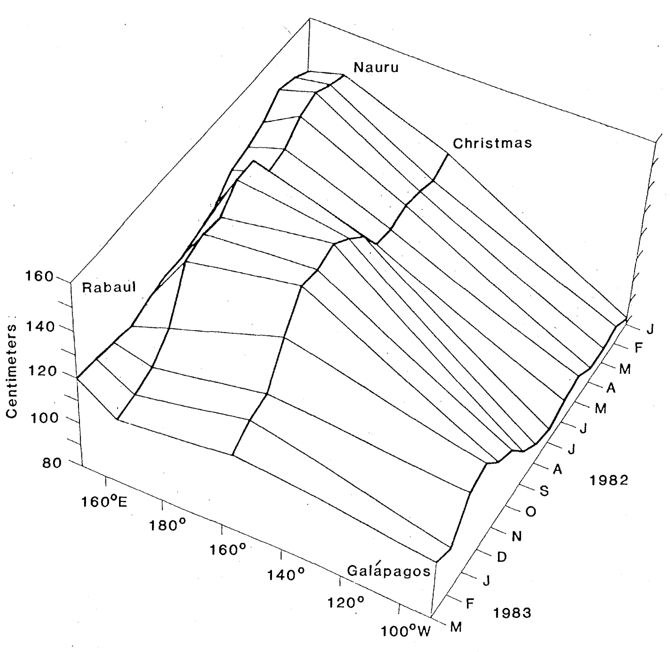

Fig. 3. The evolution of sea surface slope along the equator in the Pacific before and during the 1982–1983 El Niño (*4*). As sea level fell in the west it rose in the central Pacific and later in the eastern Pacific. The normal slope up to the west had disappeared by late 1982.

Normally the SEC is driven against a pressure force by easterly winds, but the trade winds had not yet resumed at 159°W when the SEC reappeared in January. This suggests the presence of a westward pressure force in the mixed layer, while the simultaneous return of the EUC suggests an eastward pressure force in the thermocline. The westward force near the surface is consistent with the higher sea level at Christmas Island than at Nauru. The shallow boundary between SEC and EUC indicates the importance of higher vertical-mode waves.

The eastward surface flow from October through December was probably forced by westerlies, both locally and to the west (*6*). Westerlies did not begin at 159°W until November. A purely local origin is inconsistent with the late November current maximum, since the maximum local westerlies were in December.

The anomalous northerly wind that strengthened during December 1982 and January 1983 could not have caused the return of the SEC and EUC. Meridional winds generate zonal flow primarily off the equator. Nonlinearity may lead to weak westward flow on the equator in both the mixed layer and the thermocline (*7*).

The disappearance of the undercurrent is not surprising given the intensity, fetch, and duration of the westerly wind anomalies and the dramatic changes in sea level (*8*). The sudden reappearance of the EUC and the SEC is equally dramatic but more puzzling. It will provide an interesting challenge for theoreticians and a test for numerical models.

ERIC FIRING
ROGER LUKAS
JAMES SADLER
KLAUS WYRTKI
University of Hawaii, Honolulu 96822

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2. As part of the Pacific Equatorial Ocean Dynamics Program, absolute current and temperature profiles have been measured every half-degree of latitude from 3°S to 3°N along 159°W. The average frequency has been three cruises every 2 months, with two sections per cruise.
3. Surfacing of the undercurrent refers to the ap-

pearance of eastward flow at the surface. This has been observed previously during April through September, when the trade winds weaken [K. Wyrtki *et al.*, *Science* **211**, 22 (1981)].
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9. We thank W. Austin, the crew of the R.V. *Machias*, and the technicians who made possible the longtime series of current measurements. The work was funded primarily by the National Science Foundation, with additional support from the National Oceanic and Atmospheric Administration and the State of Hawaii. This is contribution No. 1435 from the Hawaii Institute of Geophysics.

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Onshore-Offshore Patterns in the Evolution of Phanerozoic Shelf Communities

Abstract. *Cluster analysis of Cambrian-Ordovician marine benthic communities and community-trophic analysis of Late Cretaceous shelf faunas indicate that major ecological innovations appeared in nearshore environments and then expanded outward across the shelf at the expense of older community types. This onshore-innovation, offshore-archaic evolutionary pattern is surprising in light of the generally higher species turnover rates of offshore clades. This pattern probably results from differential extinction rates of onshore as compared to offshore clades, or from differential origination rates of new ecological associations or evolutionary novelties in nearshore environments.*

The broad outlines of the Phanerozoic history of skeletonized marine animals are now reasonably well known (*1*). However, comparatively little is known about how changes in global diversity relate to local environments (*2*). In light of this situation, we have analyzed marine faunal changes within environmental gradients for two pivotal intervals of the Phanerozoic: the Cambrian and Ordovician periods in the early Paleozoic and the Late Cretaceous Epoch at the end of the Mesozoic. The Cambro-Ordovician interval encompassed the origination of all three of the great "Evolutionary Faunas" that compose the Phanerozoic marine fossil record (*3*), with the appearance of the first shelly fauna (the "Cambrian Fauna") in the Early Cambrian, the rapid expansion of the more complex and diverse "Paleozoic Fauna" in the early and middle Ordovician, and, finally, the rise of early members of the modern fauna in the mid-to-late Ordovician. The Late Cretaceous interval, some 340 million years later, included a major reorganization of communities within the Modern Fauna, with the Mesozoic marine revolution bringing diversification of durophagous predators and infaunal bioturbators, decline of epifaunal suspension feeders, and increase in both global and local species richness (*1, 4*). Our analyses of the faunal changes within an environmental framework during both intervals indicate that the major new community types appeared first in nearshore settings and then expanded into offshore settings, despite higher rates of species-level evolution in the offshore habitats.

For the Cambro-Ordovician interval, a Q-mode cluster analysis was performed on 102 animal communities with well-documented macrofaunas [tabulated in (*5*)]. These communities, as illustrated in Fig. 1, were selected to give broad coverage of all marine environments from nearshore to continental slope and deep basin over the whole of the 140-million-year interval (*6*). The communities were clustered (*7*) in order to see what environments had similar ordinal–level faunas and therefore to determine where and when major faunal changes were occurring along the shelf-slope gradient. The analysis revealed four primary clusters of communities, represented by the patterned boxes in Fig. 1. The oldest two clusters correspond to the Cambrian Fauna (*3*) and are differentiated only by the dominant trilobite orders. The last appearance of the second Cambrian Fauna cluster is markedly time-transgressive, so that this grouping encompasses all shelf and slope localities in the Middle and Upper Cambrian, but then becomes restricted to progressively more offshore environments through the Ordovician—a pattern of faunal replacement first recognized by Berry (*8*). The third cluster corresponds to the Paleozoic Fauna, extending across the shelf after its initial diversification near the shoreline in the early Ordovician. Finally, a fourth primary cluster occurs in nearshore environments in the late Ordovician; this group represents the first appearance of the Modern Fauna in a distinct environmental association (*2*, p. 11; *9*). Thus, by the end of the Ordovician, the three major evolutionary faunas of the Phanerozoic oceans were arrayed in distinct community associations across the continental shelf and slope: the remnants of the Cambrian Fauna on the slope, the Paleozoic Fauna on the mid- to outer shelf, and the early members of the Modern Fauna on the inner shelf.

A parallel onshore-offshore pattern of faunal change was found in the distribution of adaptive types (as opposed to higher taxonomic groups) within the Modern Fauna over the course of the post-Paleozoic (Fig. 2). Late in the Cretaceous (Santonian-Maestrichtian) of the Gulf and Atlantic Coastal Plain and the Western Interior Provinces of North America, nearshore assemblages were dominated largely by infaunal suspension-feeders, whereas more fine-grained or midshelf assemblages (or both) were trophically mixed, containing a large complement of deposit feeders; these results correspond well to environmental patterns in modern marine benthos (*4, 10, 11*). Unlike their modern counterparts, however, Late Cretaceous mid-to-outer shelf and slope assemblages were still dominated numerically by immobile epifaunal suspension feeders (*10, 12*), the prevalent adaptive type across much of the Paleozoic and earlier Mesozoic shelf (*10, 13, 14*). These Late Cretaceous epifaunal dominants on soft substrata include pycnodont and exogyrine oysters, inoceramid bivalves, articulate brachiopods, and cyclostome and cheilostome bryozoans (*10*). In contrast, in offshore settings today immobile epifauna occur almost exclusively on hard substrata or on firm, coarse sediments that are either relict or maintained by current action (*10, 11*). Soft, offshore muds today are dominated by deposit feeders and carnivores, and lack the epifaunal suspension-feeding mode of life so prevalent in the Paleozoic and in certain Mesozoic habitats.

Several alternative evolutionary dynamics could have given rise to the onshore-offshore patterns of faunal change documented here. The patterns cannot be driven simply by differential speciation rates, because origination rates at low taxonomic levels actually tend to be higher offshore than onshore in both the Paleozoic (*15*) and post-Paleozoic (*16*). Two alternative mechanisms are:

1) *Differential extinction*. The greater extinction-resistance of nearshore clades (*16*) increases both the probability that nearshore innovations persist long