JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 92, NO. C13, PAGES 14,297–14,307, DECEMBER 15, 1987

Coastal Upwelling off Peru During Normal and El Niño Times, 1981–1984

ADRIANA HUYER, ROBERT L. SMITH, AND THERESA PALUSZKIEWICZ

College of Oceanography, Oregon State University, Corvallis

Repeated conductivity, temperature, and depth (CTD) sections were made across the continental margin off Peru at 5°S and 10°S between November 1981 and May 1984, i.e., before, during, and after El Niño of 1982–1983. Coastal sea level at Paita (5°S) and Callao (12°S) began to rise in early October 1982 and returned to normal in July 1983. Coastal winds, which are normally favorable for upwelling, remained normal during October 1982; between November 1982 and May 1983 they were weaker than normal at Talara and Paita (5°S) but stronger than normal at Callao (12°S). Between mid-March and mid-April 1983, winds at 5°S were very weak or even unfavorable for upwelling. Repeated CTD sections at 5°S show signs of active upwelling (a negative onshore surface temperature gradient and upward sloping isotherms near the coast) whenever local winds were favorable for upwelling, but not when winds were calm or unfavorable. At 10°S, winds remained favorable for upwelling throughout El Niño. At both 5°S and 10°S, the apparent source depth of upwelling waters, 50–100 m, remained the same before, during, and after El Niño; this layer is normally below the thermocline, but during El Niño it was at the top of the depressed thermocline. The upwelling that occurred during El Niño resulted only in the upwelling of warm, nutrient-poor waters. In May 1983, a CTD section at 10°S indicated that upwelling had ceased there in spite of continued strong, upwelling-favorable winds; this cessation of upwelling is attributed to an alongshore pressure gradient that persisted from mid-March to mid-June 1983, causing onshore geostrophic flow to balance the wind-driven offshore flow in the surface layer.

1. INTRODUCTION

The coastal upwelling along the entire Peru coast is driven by the southeast trade winds, which blow nearly parallel to the coast. These winds are very steady in direction with typical speeds of 3–10 m/s, and the upwelling is nearly continuous, with little of the short-term variability which dominates coastal upwelling processes at higher latitudes. As a result, Peru coastal waters are normally cool and highly productive. Only during the occasional El Niño is this ecosystem disturbed: then, cool nutrient-rich coastal waters are replaced with warm sterile waters, and the productivity collapses [*Barber and Chavez*, 1983]. Because of a paucity of suitable observations, the nature of this disturbance has not been thoroughly understood: there had been some suggestions [e.g., *Wooster and Guillen*, 1974] that upwelling-favorable winds cease during El Niño, but more recent evidence suggests that upwelling-favorable winds continue or increase [*Wyrtki*, 1975; *Enfield*, 1981], with a depressed thermocline (and nutricline) resulting in the upwelling of nutrient-depleted rather than nutrient-enriched water which now lies deeper [*Barber and Chavez*, 1983].

During recent years, intensive observations of the Peru coastal upwelling regime have been made at 5°S and 10°S (Figure 1). These observations are of particular interest because of their unique timing: a series of conductivity, temperature, and depth (CTD) sections, current meter moorings over the continental shelf, and coastal observations of wind and sea level began almost a year before the onset of the 1982–1983 El Niño and continued for almost a year after its demise. The data were collected under two separate programs with different emphases: the Peru Currents program which was sponsored by the National Science Foundation to study the currents adjacent to the Peru coast, and the EPOCS (Equatorial Pacific Ocean Climate Studies) program which was sponsored by the National Oceanic and Atmospheric Administration to study larger-scale climatic aspects of the region. Both programs included repeated CTD sections along a line crossing the equator at 85°W, and along lines intersecting the coast at 5°S and 10°S; these sections have already been used to describe the changing hydrographic conditions associated with El Niño [*Leetmaa et al.*, 1987]. CTD stations were made closer to the coast on Peru Currents cruises than on EPOCS cruises. At 10°S, the EPOCS sections had only a few stations along the 200-km line connecting 10.5°S, 80°W to the coast, while Peru Currents sections had 11 stations at intervals of 18 km. In this paper, we reexamine data from these coastal sections to shed more light on coastal upwelling and its variability.

Temperatures were recorded at current meter moorings maintained over the continental shelf at both 5° and 10°S from November 1981 until March 1985; moorings were recovered and redeployed in March 1982, November 1982, February 1983, November 1983, and May 1984 [*Paluszkiewicz and Smith*, 1984]. At each latitude, there was one mooring over the continental shelf with current meters at two depths, 50 and 100 m. The shelf mooring at 5°S was discontinued in May 1984. At 10°S, the shelf mooring from the fifth installation (November 1983 to May 1984) was lost, but a subsequent installation recorded data from May 1984 until March 1985. During the third installation (November 1982 to February 1983), water temperatures at the shelf moorings exceeded the expected range, and data were obtained only at the 100-m instrument at 10°S (and only for the first 2 months there). were made at a station over the 100-m isobath (8 km offshore) off Paita during 1982 and 1983 [*Barber and Chavez*, 1983]; these observations were used to fill the data gap in the 50-m temperature record from the 5°S shelf mooring.

Coastal wind and sea level data were compiled by *Enfield and Newberger* [1984] and *Enfield* [1987]. Winds were measured at Talara (4.6°S) and Callao (12°S) by Corporacion de

Paper number 7C0496.
0148-0227/87/007C-0496$05.00

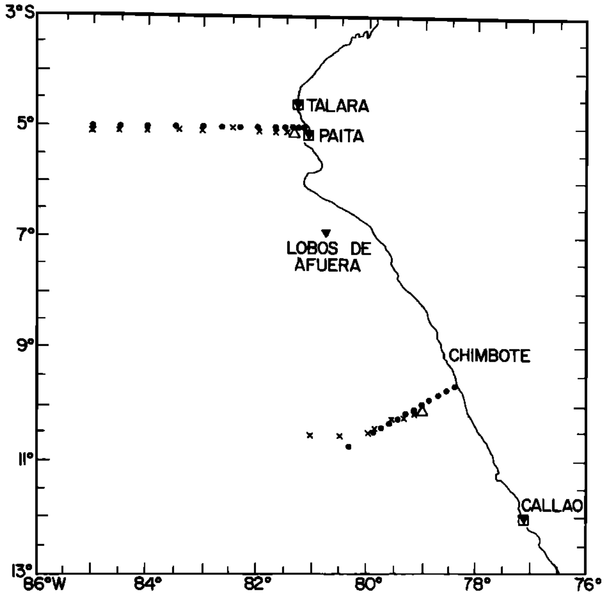

Fig. 1. Location of CTD stations along sections at 5°S and 10°S during Peru Currents (dots) and EPOCS (crosses) cruises, shelf moorings (open triangles), coastal tide gages (squares), and coastal anemometers (solid triangles).

Aviacion Civil del Peru, and at Paita (5°S) and Isla Lobos de Afuera (7°S) by Direccion de Hidrografia y Navegacion de la Marina del Peru (DHNM). Tide gages are maintained at Talara and Callao by DHNM; an additional tide gage was installed at Paita by the EPOCS program in 1982. The sea level record from the Paita tide gage was continuous from March 30, 1982, to March 31, 1984. Gaps in the Paita record were filled (using lagged regression equations) with data from Talara (November 1, 1981 to March 29, 1982; April 1, to August 7, 1984; and October 2, 1984 to February 28, 1985) or with data from El Salto at 3.9°S (August 7–31, 1984); the joined sea level record is referred to the datum at Paita. The coastal wind and sea level data, and the temperature data from the moored current meters, were all low-pass filtered (half-amplitude at 0.6 cpd) to remove diurnal and semidiurnal variations.

In this paper, we use these observations to examine how the coastal upwelling process at these two low-latitude locations on the Peru coast were modified during El Niño. First, we examine the time series of the local winds. Second, we examine the CTD sections at 5°S and 10°S before, during, and after El Niño, to see whether the observed temperature distributions are consistent with the expected response to upwelling, favorable and unfavorable winds. Third, we examine the vertical structure of the water column to see whether the upwelling waters originate below, within, or above the thermocline. Finally, we explain an apparent cessation of upwelling at 10°S in spite of continued favorable local winds.

2. THE LOCAL WINDS

Simple theory and previous observations in other upwelling regions [*Smith*, 1981] both indicate that coastal upwelling is driven by the local wind. An alongshore wind stress τ^y drives an offshore Ekman transport whose magnitude τ^y/f is inversely proportional to the local Coriolis parameter f. In a stratified ocean this offshore transport is confined to a thin surface layer with a typical depth of 10–30 m, as has been observed farther south off Peru [*Brink et al.*, 1980]. In the simplest, two-dimensional case the offshore Ekman transport is balanced by an onshore compensation flow that can occur either in a bottom Ekman layer (as observed off Africa in the winter of 1974 [*Smith*, 1981]), or at middepth (as observed at 15°S off Peru [*Brink et al.*, 1983]). The upwelling itself, i.e., the upward flow of deeper water into the surface layers, is restricted to a coastal zone whose width is of the order of the internal Rossby radius of deformation.

Although the simplest theories are for steady state upwelling, previous studies of coastal upwelling at higher latitudes [*Smith*, 1981] have shown that the magnitude of the offshore transport (and the intensity of the upwelling) varies with the local wind stress for time scales longer than the local inertial period; the offshore transport lags the wind by less than a day [*Smith*, 1981].

Time series of the low-passed alongshore component of the winds at four locations along the Peru coast are shown (Figure 2) for the November 1981 through March 1985 period which spans the entire Peru Currents measurement period. Observations began well before May 1982 when the first sign of El Niño (a noticeable surface temperature anomaly) appears in the central Pacific [*Cane*, 1983]. Local winds at all four locations continued to be normal (and favorable for upwelling) through Setpember 1982, although the reversal of trade winds in the central Pacific was definite by July 1982 [*Enfield*, 1987]. Characteristics of the local coastal winds vary from location to location: they are normally strongest at Talara, weakest at Callao, and most variable at Lobos de Afuera; some day-to-day variability occurs at all four sites, but only at Callao does it normally result in occasional reversals (Figure 2).

Sea surface temperature along the equator in the eastern Pacific was well above normal by August 1982 [*Cane*, 1983], and sea level at Paita rose rapidly from September through December at a rate of about 10 cm/month to reach a peak in early January (Figure 2). During this "onset" period, winds at Paita and Lobos remained steady, winds at Talara weakened slightly (from 7 to 5 m s^{-1}), and winds at Callao became both steadier and stronger (from 2 to 4 m s^{-1}). This strengthening can be seen very clearly in the monthly mean wind stress values presented by *Mendo et al.* [1987]. A similar strengthening of the winds at Callao occurred during the 1976–1977 El Niño [*Enfield*, 1981].

Sea level at Paita dropped rapidly in January 1983, apparently in response to a sudden weakening (in late November) of the anomalous eastward winds at 170°E in the western equatorial Pacific [*Philander and Siegel*, 1985]. After this rapid drop, it remained well above normal through February. Local winds at Paita and Talara were generally weaker and more variable during January and February; there were two brief episodes of upwelling-unfavorable winds in late January and early February. At Callao, however, upwelling-favorable winds continued stronger than normal.

By early March the reversal of the normal southeast trade winds had reached the eastern Pacific [*Enfield*, 1987], and sea level at Paita again increased rapidly (Figure 2); it remained high until early June, when the southeast trades resumed [*Enfield*, 1987]. During this interval, upwelling-favorable winds at Talara and Paita collapsed completely (Figure 2); coastal upwelling there presumably ceased for more than a month. Meanwhile, winds at Callao remained stronger than normal, favorable for upwelling. The wind at Lobos at this time

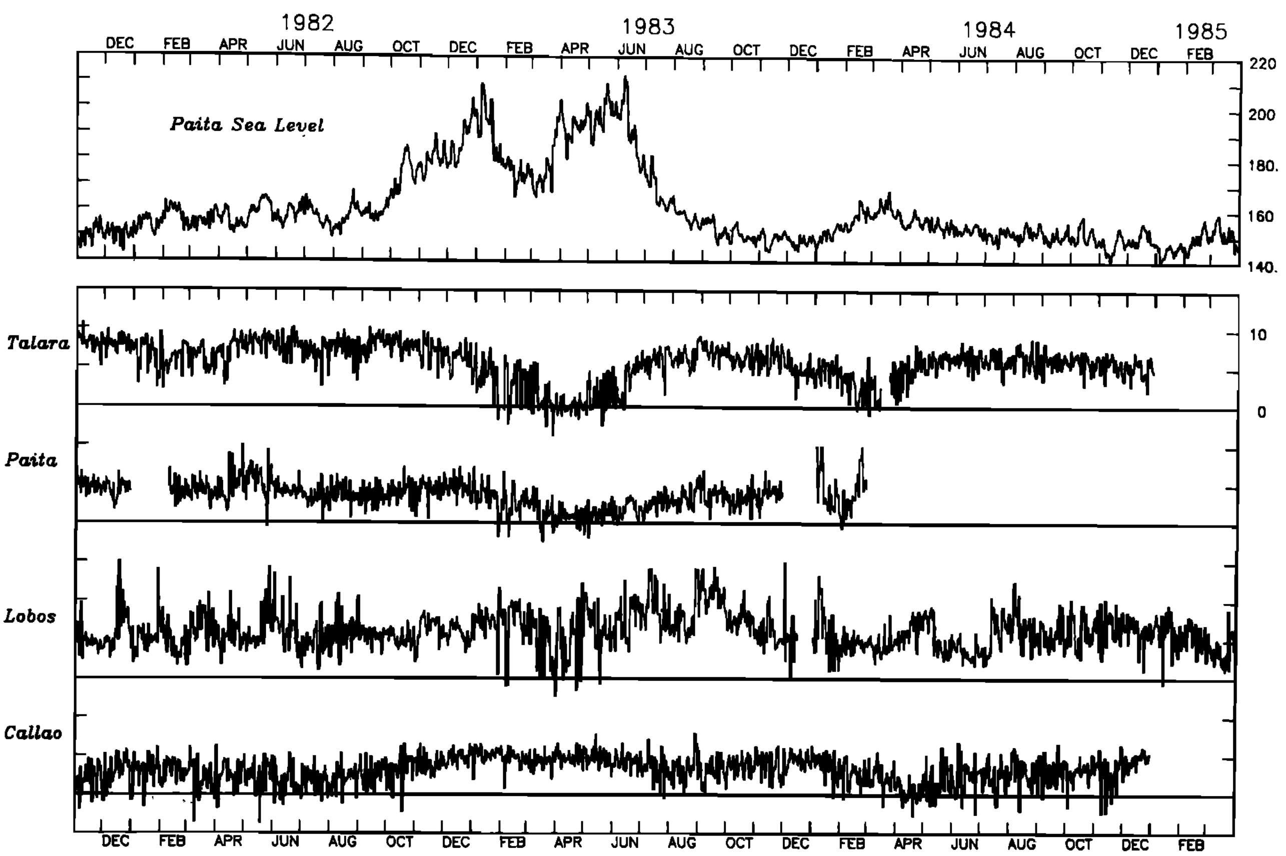

Fig. 2. Time series of the alongshore component of the low-passed wind (in meters per second) at Talara, Paita, Lobos de Afuera, and Callao, directed toward 360°T, 360°T, 335°T, and 325°T, respectively. The low-passed sea level (in centimeters) at Paita (top panel) shows the timing and duration of El Niño.

seemed to be bimodal, sometimes very weak, and sometimes stonger than normal: the record gives the impression that Isla Lobos de Afuera at 7°S was near the boundary between two different wind regimes.

During June and July, sea level at Paita dropped rapidly, and winds at all four locations gradually returned to normal (Figure 2): strengthening at Talara and Paita and decreasing at Callao. By mid-August 1983, both sea level and winds had returned to normal at all locations. Winds later in 1983 were indistinguishable from those in early 1982, before the onset of El Niño; once again, they were steady and favorable for coastal upwelling at all locations.

3. The Upwelling Signature in the Coastal Temperature Sections

Studies of coastal upwelling events at mid-latitudes [e.g., *Halpern*, 1974; *Huyer*, 1984] have shown that the near-surface temperature, salinity, and density fields in the coastal zone respond rapidly (within one or two inertial periods) to changes in the local wind stress. During and immediately after strong upwelling, isopycnals and isotherms bend up toward the coast, and surface temperature increases with distance from shore; during unfavorable winds, near-surface isopycnals and isotherms are level or sloping downward, and the offshore temperature gradient is reduced or absent. A very rapid response to changes in the wind stress was observed even at 15°S on the southern coast of Peru [*Brink et al.*, 1980]: there, the onshore-offshore current and the surface temperature lag the wind by only a day, although the local inertial period is almost 2 days. Both simple theory and observations at mid-latitudes [e.g., *Halpern*, 1974; *Huyer*, 1984] indicate that the offshore decay scale of this response is given by the internal Rossby radius of deformation, which can be inferred from the observed phase speed of internal Kelvin waves propagating poleward along the coast; a study of repeated hydrographic sections shows this is also a fundamental decay scale for variations in the temperature field at 15°S off Peru [*Huyer*, 1980].

Both of the repeated CTD lines in this study were at very low latitudes, and accordingly the local inertial period is long (5.7 days at 5°S, and 2.9 days at 10°S) compared with the time scale of some variations in the local wind stress. Calculating the internal Rossby radius of deformation ($\lambda = c/f$) from observed Kelvin wave phase speeds (c) of 2.8–3.5 m s^{-1} [*Cornejo-Rodriguez and Enfield*, this issue] gives estimates of 220–275 km at 5°S and 110–138 km at 10°S. At both latitudes, the length of the repeated CTD sections (420 km at 5°S and 200 km at 10°S) was about twice the local Rossby radius and much greater than the shelf width at 5°S (30 km) and twice the shelf width at 10°S (100 km). At both latitudes, CTD sections were made during the abnormal winds associated with El Niño, as well as during the normal, steady, upwelling-favorable winds. The full (0–1000 m) temperature and salinity distributions between the coast and 85°W have been presented by *Leetmaa et al.* [1987]. To focus on the upwelling process in these sections, we display only the upper layer (0–250 m) temperature distributions with time series of local or nearby winds in Figures 3–6.

At 5°S, the six CTD sections which preceded or followed El Niño (before October 1982 or after August 1983) all show the 18° and 20°C isotherms sloping gently upward to intersect the

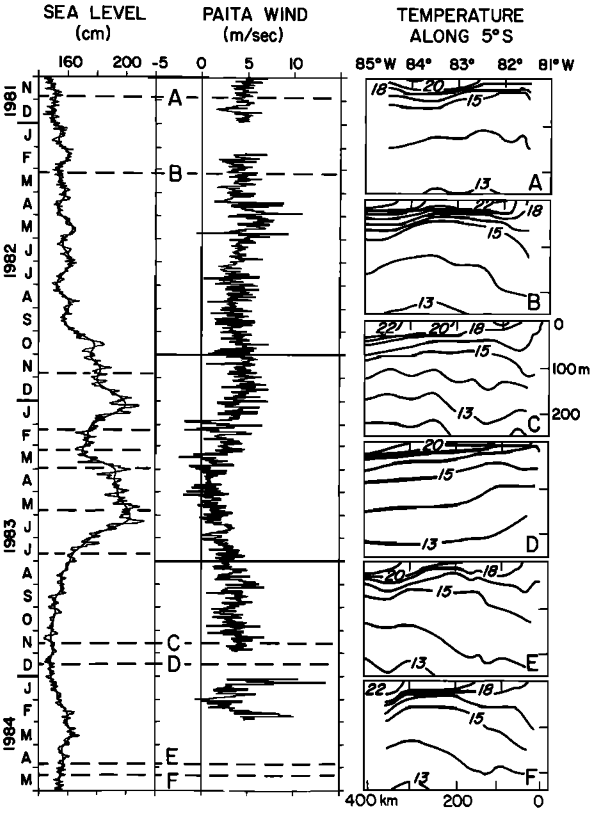

Fig. 3. Temperature distributions in the upper 250 m along 5°S, from sections made before and after El Niño, shown with time series of the sea level and wind at Paita. Dashed lines indicate the time CTD sections were made.

surface within 200 km of the coast, as expected from the steady, upwelling-favorable winds (Figure 3). The coldest water at the surface inshore lies at a depth of 50–75 m offshore; it seems to originate in or below the thermocline. Sections made at this latitude during March–May 1977 also show upwelling source waters lying at about 60 m, in the lower thermocline [*Fahrbach et al.*, 1981]. As the thermocline approaches within 75 km of the coast, isotherms within it diverge, with deeper isotherms bending down while shallower ones bend up; this isotherm divergence is believed to be a signature of the poleward undercurrent over the continental margin [*Leetmaa et al.*, 1987]. Below the thermocline lies a broad thermostad (13°–15°C) in which the temperature gradient is very small.

During El Niño, between November 1982 and July 1983, the structure of the CTD sections at 5°S, and the strength of the winds at Talara and Paita, were variable (Figure 4). CTD sections made during strong upwelling-favorable winds (i.e., in November 1982, early March 1983, and July 1983) all indicate active upwelling, i.e., isotherms from depths of 50–75 m offshore bend upward to intersect the surface near the coast. However, these isotherms now have temperatures between 22° and 26°C. These warm upwelling waters seem to originate in the upper part of the thermocline, which has been suppressed and thickened by El Niño. The remaining CTD sections (in February 1983, late March 1983, and late May 1983) all show inshore surface waters are as warm as those offshore, indicating that upwelling has temporarily ceased; all three of these sections show isotherms in the upper layers nearly level or sloping down toward the coast (Figure 4). In comparing these sections to the local winds, we average the time series of the wind over about 6 days, since we do not expect an upwelling response to wind fluctuations with periods shorter than the local inertial period. The first of the "non-upwelling" CTD sections was made at the beginning of February, during the second of two 5- to 6-day episodes of reversed winds at Talara and Paita. The second section was made at the end of March, when upwelling-favorable winds were absent (at Paita) or very weak (1–2 m s^{-1} at Talara) for more than a month. The third was in late April, when winds were favorable for upwelling but still very weak (2–3 m s^{-1} at both Talara and Paita). The full suite of sections at 5°S suggests that the coastal upwelling there was driven entirely by the local winds: upwelling occurred when the winds blew equatorward, and it ceased when they did not, regardless of whether El Niño was present.

A similar comparison between the repeated CTD sections at 10°S and winds is made in Figures 5 and 6. The nearest coastal wind observations were at Islas Lobos de Afuera (at 7°S) and at Callao (12°S). Of these, the Callao data are more likely to be representative of the coastal winds at 10°S [*Enfield*, 1981; *Enfield and Newberger*, 1984]. The six sections made before and after El Niño (i.e., before September 1982 or after August 1983) are all consistent with active upwelling of cool (16°–20°C) water from depths of 75–100 m (Figure 5). This upwelling is most obvious in the Peru Currents sections, which included stations over the shelf, but upward sloping isotherms and a positive offshore surface temperature gradient are also visible in the three EPOCS sections which ended near the shelf break.

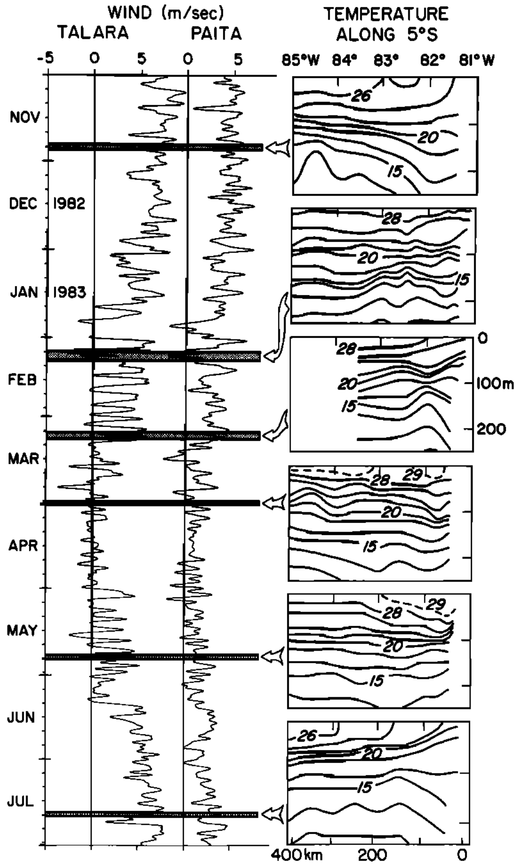

Fig. 4. Temperature distributions in the upper 250 m along 5°S, from sections made during El Niño, shown with time series of the wind at Talara and Paita.

The six 10°S sections during El Niño were all made at times of moderate or strong upwelling-favorable winds at both Lobos de Afuera and Callao (Figure 6). The three sections in February and March 1983 show 24°–26°C isotherms bending upward from depths of 50–75 m to intersect the surface over the shelf, indicating active upwelling of warm waters from the upper portion of a depressed thermocline. The two sections in November 1982 and April 1983 also suggest active upwelling, although they do not approach close enough to shore to be sure. The EPOCS section made in May 1983 indicates that upwelling had ceased, in spite of continued favorable winds at both Callao and Lobos. A pair of CTD stations (stations 70 and 71 of EP3-83-RS) over the shelf and upper slope off Callao on June 1, 1983, both showed a 50-m-thick surface layer with a temperature of about 26.4°C [*Roffer et al.*, 1984], indicating that upwelling had ceased there also. This anomalous cessation of upwelling will be discussed further in section 5.

4. Changes in Thermal Structure and Stratification

Comparison of the "normal" (Figures 3 and 5) and the "El Niño" (Figures 4 and 6) coastal temperature sections shows anomalous structure during El Niño at both 5°S and 10°S: the surface layer was much warmer (by 4°C or more), the thermocline (between 15° and 22°C) was much thicker, and there was no longer a thermostad between 13° and 15°C. The full (0–1000 m) sections show that the thermostad was completely absent in February 1983 and that it was not restored to its normal thickness until 1984 [*Leetmaa et al.*, 1987].

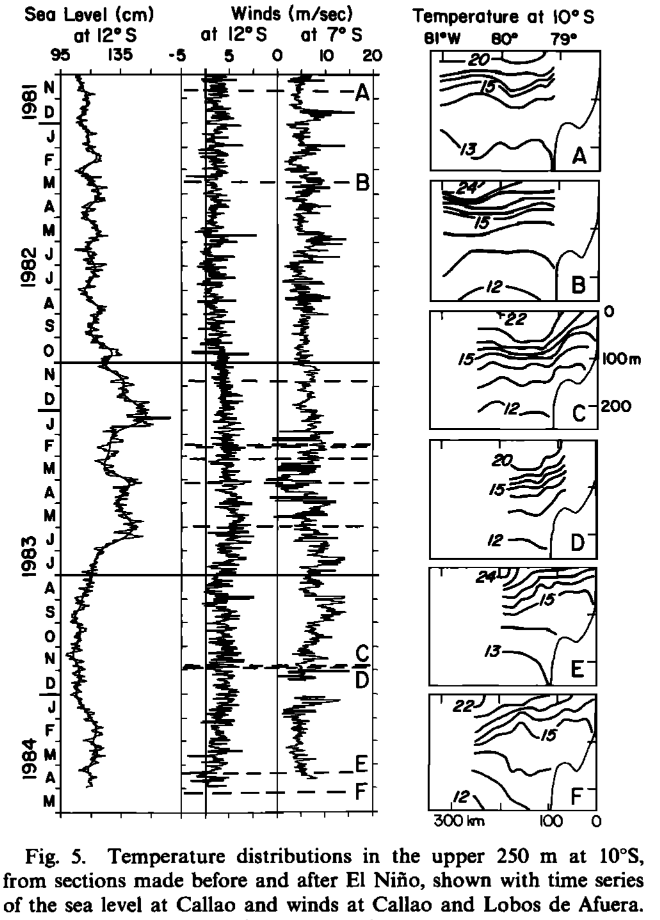

Fig. 5. Temperature distributions in the upper 250 m at 10°S, from sections made before and after El Niño, shown with time series of the sea level at Callao and winds at Callao and Lobos de Afuera. Dashed lines indicate the time CTD sections were made.

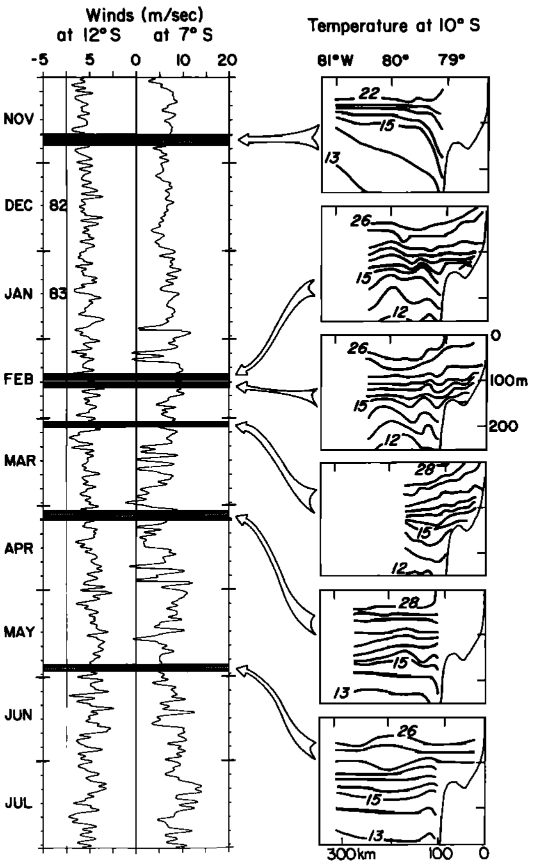

Fig. 6. Temperature distributions in the upper 250 m along 10°S, from sections made during El Niño, shown with time series of the wind at Callao and Lobos de Afuera.

From the discussion in the previous section, it appears that the depth of the upwelling source waters (between 50 and 100 m at both latitudes) remained fairly steady before, during, and after El Niño. However, the vertical structure of the water column changed significantly over this period. These changes have the potential of affecting the "quality" of the water which upwells, i.e., they may affect the productivity of the upwelling ecosystem. The change in vertical structure can be seen very clearly in profiles of the Brunt-Vaisala frequency N, which is a measure of the static stability ($N^2 = g\rho^{-1}\partial\rho/\partial z$, where ρ is the density, z is the depth increasing downward, and g is the acceleration due to gravity). For Peru Currents cruises, values of N were calculated at 10-dbar intervals from the 2-dbar processed CTD data files by fitting a least squares estimate of the specific volume anomaly gradient over a centered 20-dbar interval. For EPOCS cruises, N was calculated from consecutive pairs of the published temperature and salinity values (at intervals of 10 dbar above 300 dbar and intervals of 50 dbar below 300 dbar [*Roffer and Leetmaa*, 1982; *Roffer et al.*, 1984]).

In Peru coastal waters the value of N is roughly proportional to the vertical temperature gradient: high values correspond to a thermocline, and very low values indicate a thermostad. For each latitude, we show profiles at a single location about one local Rossby radius from shore, with the time series of temperature at depths of 50 and 100 m obtained from moorings over the midshelf at 5°S and over the outer shelf at 10°S.

The profiles of N at 5°S (Figure 7) obtained before and after El Niño are very similar. They all show a very thin (<40 m)

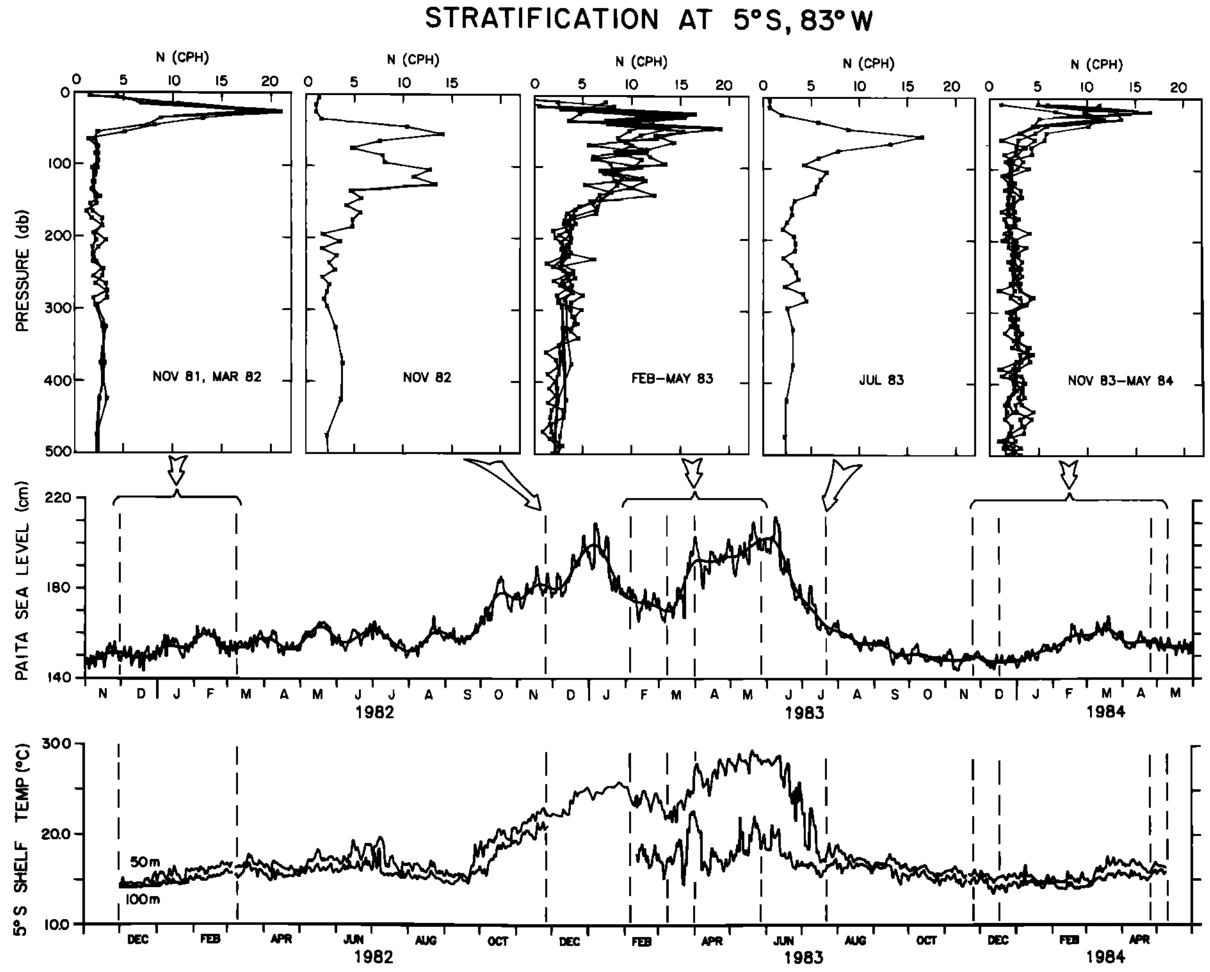

Fig. 7. Vertical profiles of the Brunt-Vaisala frequency (N) before, during, and after El Niño at 5°S, 83°W, about one Rossby radius offshore from Paita, and time series of the low-passed sea level at Paita and low-passed temperature at depths of 50 and 100 m at the 5°S midshelf mooring. Dashed lines indicate the timing of the CTD stations.

peak in N, reaching a maximum value of about 15 cph at a depth of about 30 m. The small (<5 cph) N values above this peak indicate that there is a thin surface mixed layer. The layer between 50 and 100 m which seems to be the source of upwelling water lay below the peak, i.e., below the thermocline. The very small values (2 cph) of N between 75 and 200 m indicate the thermostad. During these normal periods, both current meters on the shelf (at depths of 50 and 100 m) were also deeper than the thin thermocline, and both recorded low temperatures of 14° to 18°C (Figure 7).

The profile in November 1982, soon after the onset of El Niño, shows a deeper surface mixed layer, and a split thermocline; the lower thermocline is at depths normally occupied by the thermostad (Figure 7). The shelf current meters show temperatures at both 50 and 100 m were rising steadily during October and November. During the subsequent mooring period (December to February), the 100-m instrument failed to record any data, and the 50-m instrument showed only that temperature always exceeded 20.5°C. Daily hydrographic casts over the 120-m isobath off Paita [*Barber and Chavez*, 1983] were used to fill in the 50-m temperature record; these show that the temperature of the water at 60 m continued to increase until February. During this period, upwelling water originated in the upper thermocline.

The 5°S profiles taken between February and May 1983, during El Niño, show that the peak in N was much broader, spread over a depth range of 30 to 150 m (Figure 7). Maximum values were somewhat smaller than those observed before and after El Niño. The surface mixed layer was still quite thin (<30 m), and the thick thermocline was centered at a depth of about 80 m. High values of N penetrated to the layer (50–75 m) which normally supplies the upwelling water, and to depths (75–150 m) normally occupied by the thermostad. Even if local winds had not collapsed, surface waters inshore would have been very warm and low in nutrients. The 50-m current meter on the shelf is just above the peak in N (i.e., in the upper thermocline), while the 100-m instrument is below the peak, in the lower thermocline; they record quite different temperatures during this period.

The temperature difference between the 50- and 100-m instruments over the shelf at 5°S decreased during June and early July (Figure 7). By late July 1983 the peak in N had sharpened, though it was still deeper than normal; by now some of the water upwelling along the coast at 5°S may have had its source in the lower thermocline. By November 1983, the thermocline had shoaled, and the stratification had returned to normal.

The Brunt-Vaisala frequency profiles at 10°S (Figure 8) from CTD casts made before and after El Niño show that maximum N values occured in the upper 75 m; the peak was

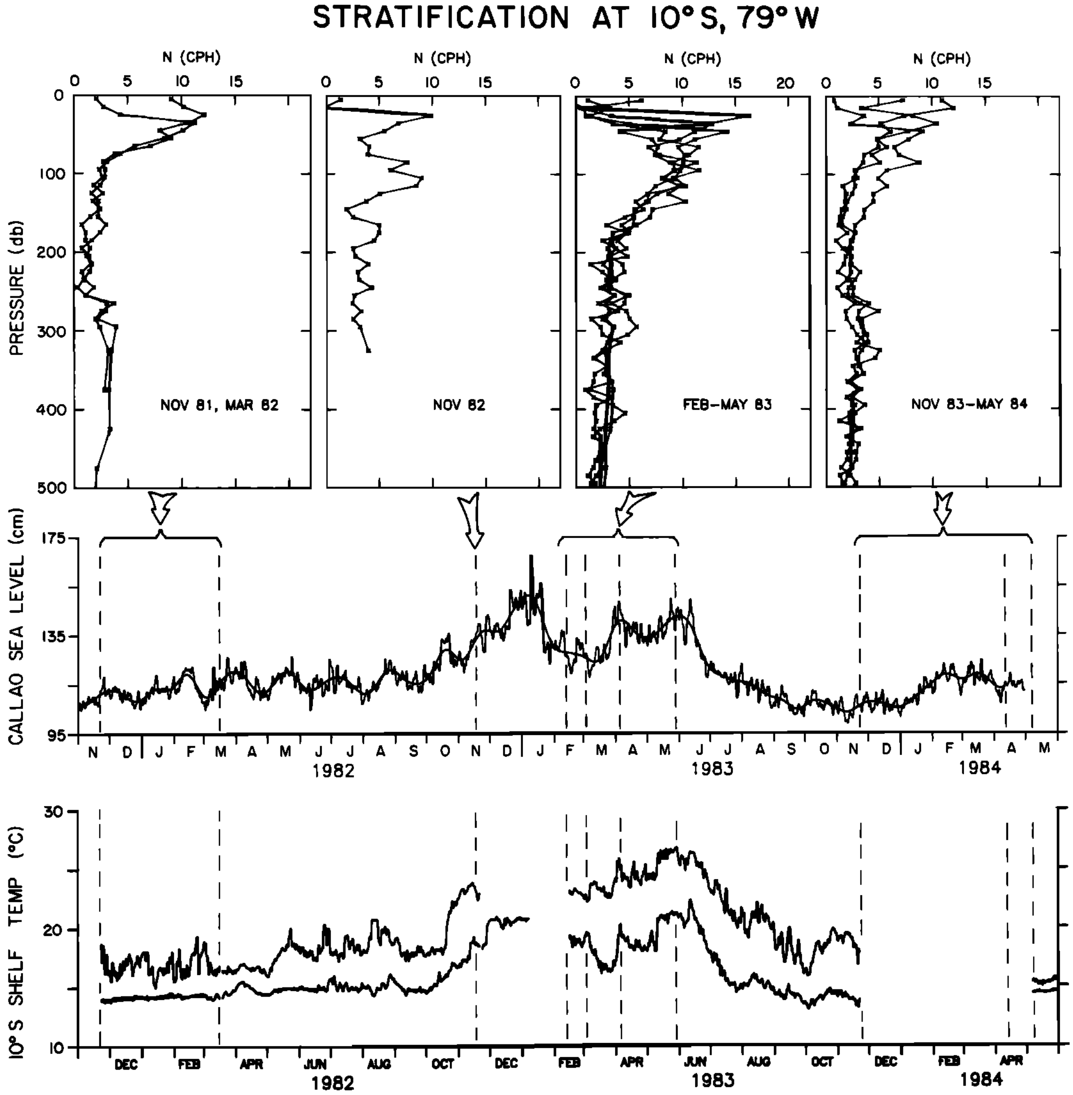

Fig. 8. Vertical profiles of the Brunt-Vaisala frequency (N) before, during, and after El Niño at 10.1°S, 79.1°W, about one Rossby radius offshore, and time series of the low-passed sea level at Callao and low-passed temperature at depths of 50 and 100 m at the 10°S outer shelf mooring. Dashed lines indicate the timing of the CTD stations.

not as thin and sharp as at 5°S. Surface values of N were moderate; the surface layer was not thoroughly mixed, even in the upper 10 m. At this latitude, the minimum values of N (the thermostad) occurred between 150 and 250 m. Of the two current meters moored over the outer shelf, the 50-m instrument was within the thermocline (close to the peak N values) and recorded variable temperatures between 16° and 20°C; the 100-m instrument was below the thermocline and recorded fairly steady, cool temperatures of 14°–16°C.

During October and November, the temperature at 100-m depth over the outer shelf at 10°S rose steadily from 15° to 20°C (Figure 8), at a rate consistent with the increased poleward advection associated with the onset of El Niño [*Smith*, 1983]. The abrupt rise in the 50-m temperature on October 19–22 indicates a deepening thermocline. By late November, the N profile had two peaks, indicating a deep thermocline at 100 m as well as a shallow one at 30 m. Temperatures remained high for the entire deployment period from late November to early February, always exceeding 22°C (full scale) at 50 m, and exceeding 22°C at 100 m from January 9, on.

The N profiles at 10°S between February and May 1983, during El Niño, show small values of N at the surface (Figure 8), indicating that the surface mixed layer had deepened to about 20 m. Maximum values of N tended to be deeper than normal, and the broad peak (between 50 and 150 m) was centered at a depth of about 100 m. There was no obvious layer of minimum N, i.e., no thermostad, at this time. Both of the current meters on the shelf were within or above the thermocline; both record warm and variable temperatures.

Beginning in mid-June, the temperature at both depths decreased gradually. By August, the 100-m instrument must have been below the thermocline, since it was recording temperatures of about 15°C. The temperature difference between 50 and 100 m remained large through November 1983, indicating that the 50-m instrument was still in the middle or upper thermocline. By May 1984 the thermocline was shallower than 50 m: both instruments were recording temperatures of about 15°C. We cannot be more specific about the timing of the thermocline shoaling, since the 10°S shelf mooring for the November 1983 to May 1984 period was lost.

At both latitudes the thermocline was deeper and thicker than normal during the entire El Niño period, from at least

TABLE 1. Comparison of Steric Height of the Sea Surface Relative to 500 dbar at Selected CTD Stations at 5°S and the Low-Passed Sea Level at Paita

	Steric Height at				
Date	81.5°W	82°W	83°W	Sea Level	*N*
Nov. 28–29, 1981	083.8	085.6	089.3	151.4	109.
March 7–9, 1982	088.3	090.6	088.8	155.0	509.
Nov. 26–27, 1982	118.9	122.7	120.2	187.0	1565.
Feb. 8–9, 1983	107.8	109.0	109.4	177.6	1861.
March 7–8, 1983	099.8	102.8	106.6	170.6	1970.
March 31 to April 1, 1983	126.1	123.4	117.0	202.5	2064.
May 25–26, 1983	130.0	129.4	124.9	202.5	2285.
Nov. 19–20, 1983	084.1	085.3	083.6	151.2	2996.
Dec. 17–18, 1983	080.8	081.3	084.2	148.1	3108.
April 25–26, 1984	090.5	089.6	089.0	153.3	3625.
May 9, 1984	089.2	085.5	088.7	155.0	3679.
March 22–24, 1985	086.2	084.6	089.0	151.0	4951.

N is the line number of the 6-hourly sea level value, with $N = 1$ corresponding to 0000, November 1, 1981.

November 1982 through June 1983. During this period, any water that upwelled along the coast at either latitude would have originated at the top of the depressed thermocline, i.e., the upwelling water would have been very warm. The depressed thermocline also represents a depressed nutricline [*Barber and Chavez*, 1983, Figure 6]. Thus water upwelling during this period would have been much less productive than normal.

5. SUPPRESSION OF UPWELLING AT 10°S IN MAY 1983?

In spite of favorable winds at both Lobos de Afuera (7°S) and Callao (12°S), upwelling was not observed in the May 1983 section at 10°S. In principle, an alongshore pressure gradient ($\partial p/\partial y$) can result in onshore geostrophic flow, which may effectively cancel the offshore Ekman transport caused by the wind stress [*Thompson*, 1987].

To determine whether there was a significant sea level slope along the coast, we used CTD data to determine the steric height of coastal tide gages relative to the 500-dbar surface. Repeated CTD sections across the continental margin were available at 5°S and 10°S; the coastal tide gages are situated at Paita (5°S) and Callao (12°S). Steric height data from CTD stations along sections at 5°S and 10°S were compared directly with the simultaneous low-passed tide gage data from Paita (Table 1) and Callao (Table 2), respectively. However, sea level fluctuations are known to propagate poleward along the Peru coast at a phase speed of about 3 m/s, with generally high coherence over alongshore separations of several hundred kilometers [*Romea and Smith*, 1983; *Cornejo-Rodriguez and Enfield*, this issue]. Since the coastal end of the 10°S section is 250 km from Callao, we assumed that the coastal sea level at 10°S was the same as the low-passed sea level observed at Callao one day later. We thus compared the steric height data from CTD stations at 10°S with the low-passed sea level at Callao a day later (Table 2); this 1-day lag yielded slightly higher correlations than the unlagged comparison. At both latitudes the internal Rossby radius of deformation is as great as or greater than the shelf width, and we made no attempt to extrapolate the 500-dbar reference level into shallower water. At both latitudes, we examined steric height data from CTD stations at a few different offshore locations (Tables 1 and 2); in each case the station nearest the 500-m isobath gave the best correlation with the coastal sea level.

Comparison of sea level data with the steric height at 5°S, 81.5°W indicates that a steric height value of 9.0 $m^2\ s^{-2}$ relative to the 500-dbar surface corresponds to a coastal sea level value of 156.8 cm at Paita (Figure 9 (left)). Similarly, comparison of Callao sea level with the steric height at D-6 (the first CTD station beyond the 500-m isobath) at 10°S indicates that a steric height of 9.0 $m^2\ s^{-2}$ corresponds to a coastal sea level value of 112.5 cm at Callao (Figure 9 (right)).

Figure 10 shows the time series of coastal sea level at both locations, with steric height values superimposed by assuming that $\Delta D_{0/500} = 9.0\ m^2\ s^{-2}$ corresponds to 112.5 cm at Callao and 156.8 cm at Paita. These time series of sea level at Paita and Callao can be used as proxies for continuous estimates of the steric height just beyond the continental shelf at 5°S and 10°S, respectively. Also shown in Figure 10 is the time series of the difference in sea surface height relative to the 500-dbar surface (Figure 10); this sea level difference shows considerable variability at periods of 5–10 days, particularly between November 1982 and July 1983, during El Niño. Since much of this variability is associated with coastal-trapped waves propagating through the region [*Cornejo-Rodriguez and Enfield*, this issue] and not related to the coastal upwelling process, the data were filtered again (half-amplitude of 0.033 cpd) to yield "very low-passed" time series (Figure 11) of the steric height at the two locations.

During most of the November 1981 to April 1985 period, both before and after El Niño, the sea surface was at nearly the same height at both locations, standing only a few centimeters higher at 10°S than at 5°S (Figure 11). During the first few months of El Niño (November to February), the sea surface was slightly higher at 5°S than at 10°S, by as much as 5 cm in October and early November. Between mid-April and late May, when winds were very weak at Paita and Talara (Figure 2), the sea surface was about 15 cm higher at 5°S than at 10°S.

A large-scale average sea level slope of this magnitude would indicate an onshore geostrophic flow at 10°S of

$$u_g = -(g/f)\Delta h/\Delta y = 9.5\ \text{cm s}^{-1}$$

TABLE 2. Comparison of Steric Height of the Sea Surface Relative to 500 dbar at Selected CTD Stations at 10°S and the Low-Passed Sea Level at Callao

	Steric Height at			Unlagged		Lagged 1 Day	
Date	D-6	D-9	D-11	Sea Level	*N*	Sea Level	*N*
Nov. 21–22, 1981	89.1	89.0	88.2	109.1	83.	112.3	87.
March 16–17, 1982	85.7	84.1	84.9	117.1	544.	113.5	548.
Nov. 21–22, 1982	105.9	99.8	97.2	135.2	1547.	134.0	1551.
Feb. 14–15, 1983	106.5	108.3	103.8	125.1	1884.	122.7	1888.
Feb. 16–17, 1983	103.7	107.9	108.0	119.2	1893.	119.3	1897.
March 2, 1983	103.6	107.0	108.3	127.3	1947.	126.7	1951.
April 5–6, 1983	115.5	116.4	123.2	144.2	2085.	143.2	2089.
May 30, 1983	116.5	116.3	120.4	144.4	2303.	145.5	2307.
Nov. 24, 1983	86.9	87.8	85.7	103.4	3016.	105.6	3020.
Dec. 3, 1983			87.6	106.2	3050.	102.8	3054.
Dec. 19, 1983		86.8	87.2	108.5	3116.	105.0	3120.
April 9, 1984	85.7	87.7	91.6	109.6	3559.	112.2	3563.
May 5–6, 1984	87.6	87.5	87.0	113.1	3665.	112.6	3669.
March 16–17, 1985	84.8	84.9	83.2	109.8	4925.	109.3	4929.

N is the line number of the 6-hourly sea level value in the tide gage record, with $N = 1$ corresponding to 0000, November 1, 1981.

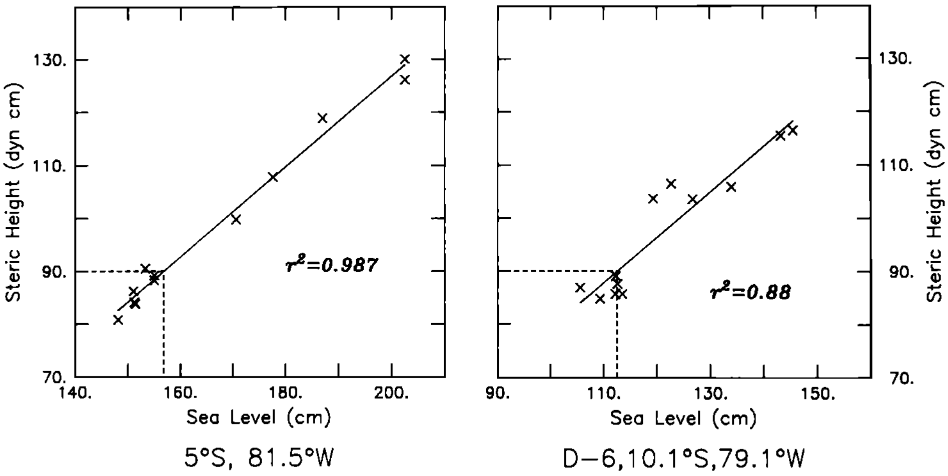

Fig. 9. Steric height (relative to 500 dbar) at the first station beyond the 500-m isobath plotted as a function of low-passed coastal sea level. (Left) Steric height at 5°S, 81.5°W versus simultaneous sea level at Paita. (Right) Steric height at 10.1°S, 79.1°W versus sea level at Callao one day later.

where Δh is the sea level difference, Δy is the alongshore distance (620 km) between the steric height measurements, and f is the Coriolis parameter at 10°S. Although smaller-scale alongshore pressure gradients and associated onshore/offshore flows might also exist, it is worth comparing this large-scale onshore flow to the wind-driven Ekman current. During the April-May 1983 period, winds were strong at Callao, averaging about 6 m s^{-1} (Figure 2). If these winds were also experienced at 10°S, they would result in an offshore Ekman transport of

$$M_E = \tau^y/f = 2.7 \times 10^4 \text{ g s}^{-1}$$

where τ^y is the alongshore wind stress (0.675 dyn cm^2). If this Ekman transport were restricted to a surface layer with a thickness $H = 30$ m, the vertically averaged offshore component of the Ekman velocity would be

$$u_E = M_E/(\rho H) = 9 \text{ cm s}^{-1}$$

Thus the offshore Ekman velocity driven by the upwelling favorable winds was about the same size as the onshore geostrophic velocity associated with the large-scale alongshore sea surface slope.

The vertical profiles of the onshore component of the geostrophic velocity obtained from the 5°S–10°S CTD station

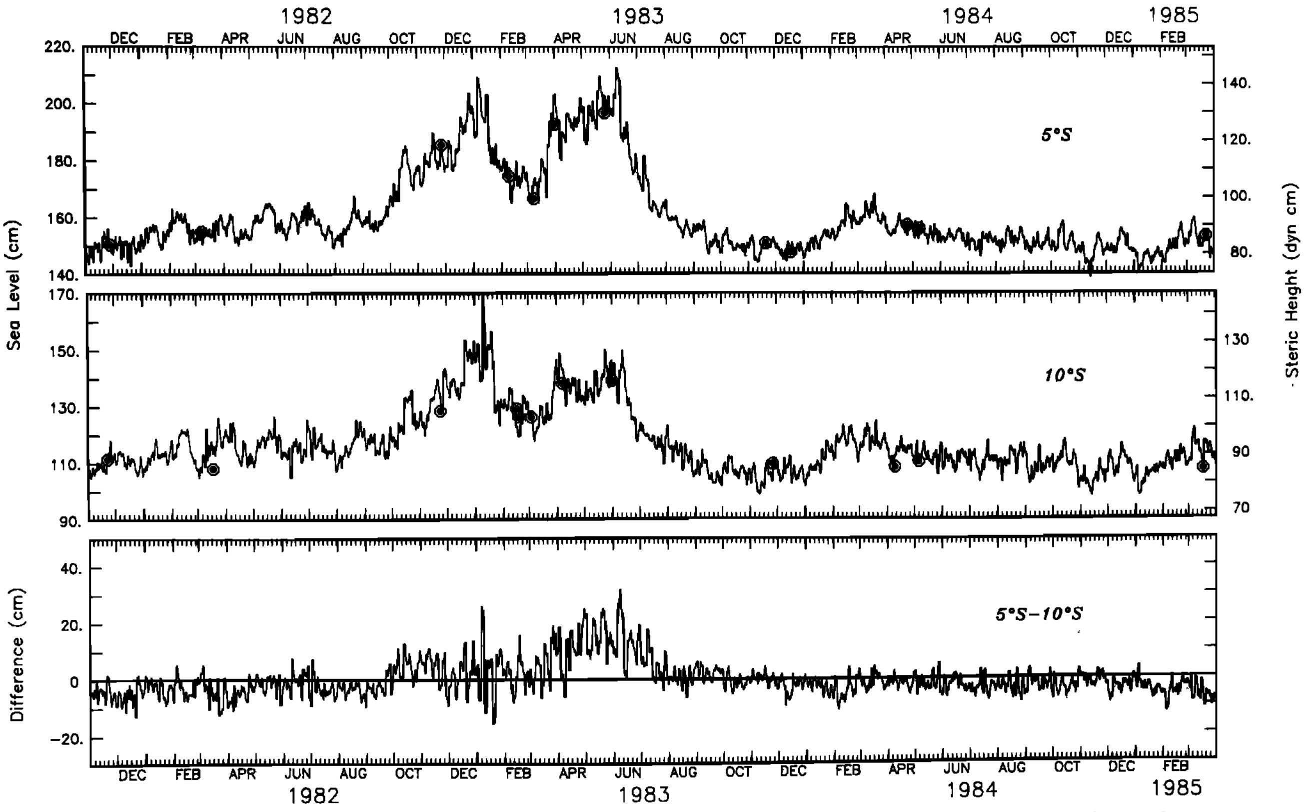

Fig. 10. Steric height of the sea surface relative to 500 dbar at 5°S and 10°S, superimposed on time series of coastal sea level at 5°S and 12°S, respectively, and the sea level difference between 5°S and 10°S assuming the 500-dbar surface is level.

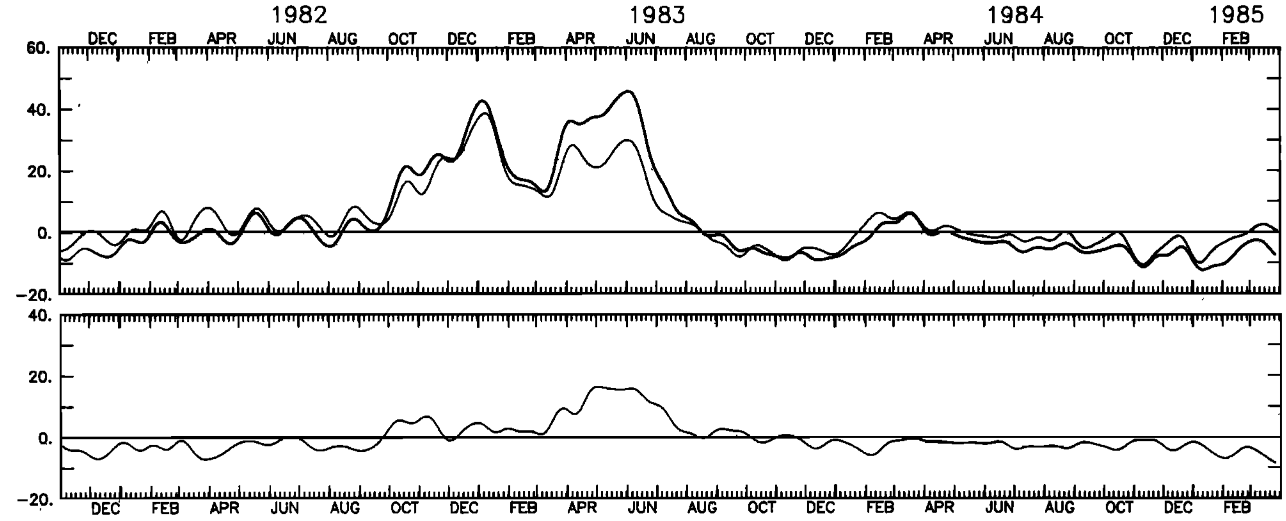

Fig. 11. Very low-passed time series of coastal sea level at 5°S (heavy line) and 12°S (lighter line), both referred to 500 dbar, and of the sea level difference relative to 500 dbar.

pairs show that only during three of the surveys was the onshore geostrophic flow significant ($u > 5$ cm s^{-1}): in November 1982 and in April and May 1983. In Figure 12 we show the vertical profiles of the onshore geostrophic flow computed at 10°S relative to 500 dbar, using all the CTD station pairs from 5°S and 10°S. The November 1982 period of strong large-scale onshore flow occurred at the onset of El Niño during the period of intense warming at 10°S (Figure 8). During April and May 1983 the onshore flow is large (> 5 cm s^{-1}) only above 50 m and would effectively suppress the offshore Ekman transport. Unfortunately, the shallowest current meter was at 58-m depth, below the depth of the enhanced onshore flow. These onshore geostrophic velocity profiles are consistent with approximately zero net offshore velocity in the surface layer, and the suppression of coastal upwelling during April and May 1983.

6. CONCLUSIONS

During El Niño of 1982–1983, local winds remained normal for at least a month after coastal sea levels and coastal temperatures began to rise in early October 1982. At the height of El Niño, from February through May 1983, winds were stronger than normal at Callao (12°S) but much weaker than normal at Talara and Paita (5°S); the winds which normally drive coastal upwelling at 5°S collapsed completely for about a month in March and April 1983.

Repeated CTD sections at 5°S showed upward sloping isopycnals and a negative onshore surface temperature gradient near (O(100 km)) the coast, features indicative of active upwelling, whenever local winds were favorable for upwelling. These traits of upwelling were not observed when local winds were calm or unfavorable. The apparent source depth of upwelling water remained the same (i.e., 50–100 m) before, during, and after El Niño. However, this source normally lies below the thermocline, so that upwelling waters are normally cool, high in nutrients, and productive. During El Niño, the thermocline was both deeper and thicker than normal; any upwelling that occurred resulted only in the upwelling of warm, nutrient-poor waters from the top of the depressed thermocline.

Sections at 10°S showed upwelling continued through most of El Niño, in response to the stronger, upwelling-favorable winds at this latitude. As at 5°S, waters upwelling before and after El Niño were cool, originating in the lower part of the thermocline. Waters upwelling during El Niño originated at about the same depth, which now was occupied by the top of the deeper thermocline. In May 1983 a CTD section indicated that upwelling at 10°S had ceased in spite of continued strong and favorable local winds. This cessation of upwelling occurred because the wind-induced offshore flow in the surface layer was balanced by an onshore geostrophic flow associated with an alongshore pressure gradient; the steric height near the shelf break (relative to 500 dbar) was significantly greater at 5°S than at 10°S at this time. The cause of this alongshore pressure gradient is not known; it may be related to the structure of the larger-scale wind field. Coastal tide gage records indicate that the alongshore pressure gradient, which suppressed offshore flow in the surface layer, was present only

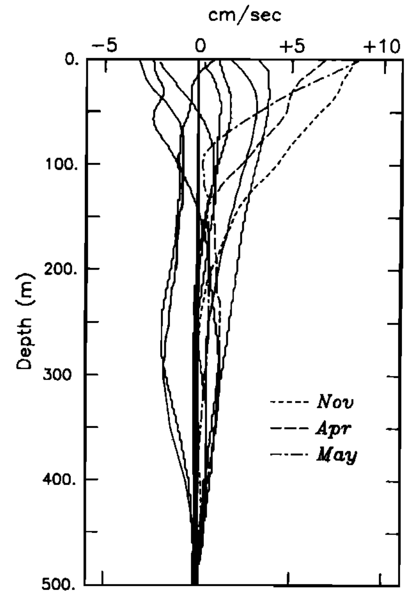

Fig. 12. Vertical profiles of the onshore geostrophic velocity at 10°S calculated from pairs of CTD stations at 5°S, 81.5°W and 10.1°S, 79.1°W. Profiles for November 1982, early April 1983, and late May 1983 are dashed.

from mid-March through mid-June 1983; upwelling at 10°S apparently continued during the rest of El Niño.

Acknowledgments. We are grateful to Dave Enfield for providing the wind and sea level data, and to Francisco Chavez for providing the triweekly hydrographic data at Paita. The EPOCS CTD sections were obtained by Ants Leetmaa and Dave Behringer. Priscilla Newberger, Jane Fleischbein, and Henry Pittock assisted in the data processing and analysis. We owe special thanks to Rory Thompson for sharing his ideas on the role of alongshore pressure gradients in upwelling regimes. This work is funded by the National Science Foundation through grants OCE-8315014 and OCE-8709930.

References

Barber, R. T., and F. P. Chavez, Biological consequences of El Niño, *Science, 222,* 1203–1210, 1983.

Brink, K. H., D. Halpern, and R. L. Smith, Circulation in the Peruvian upwelling system near 15°S, *J. Geophys. Res., 85,* 4036–4048, 1980.

Brink, K. H., D. Halpern, A. Huyer, and R. L. Smith, The physical environment of the Peruvian upwelling system, *Progr. Oceanogr., 12,* 285–305, 1983.

Cane, M. A., Oceanographic events during El Niño, *Science, 222,* 1189–1195, 1983.

Cornejo-Rodriguez, M. P., and D. B. Enfield, Propagation and forcing of high-frequency sea level variability along the west coast of South America, *J. Geophys. Res.,* this issue.

Enfield, D. B., Thermally driven variability in the planetary boundary layer above Lima, Peru, *J. Geophys. Res., 86,* 2005–2016, 1981.

Enfield, D. B., The intraseasonal oscillation in eastern Pacific sea levels: How is it forced?, *J. Phys. Oceanogr.,* in press, 1987.

Enfield, D. B., and P. A. Newberger, Peru coastal winds in 1982–1983, *Proceedings of the Ninth Annual Climate Diagnostic Workshop,* pp. 147–156, U.S. Dep. of Commer., Nat. Oceanic and Atmos. Admin., Washington, D. C., 1984.

Fahrbach, E., C. Brockmann, N. Lostaunau, and W. Urquizo, The northern Peruvian upwelling system during the ESACAN experiment, in *Coastal Upwelling,* F. A. Richards, *Coastal and Estuarine Sci. Ser.,* vol. 1, edited by F. A. Richards, pp. 134–145, AGU, Washington, D. C., 1981.

Halpern, D., Structure of a coastal upwelling event observed off Oregon during July 1973, *Deep Sea Res., 23,* 495–508, 1974.

Huyer, A., The offshore structure and subsurface expressions of sea level variations off Peru, 1976–1977, *J. Phys. Oceanogr., 10,* 1755–1768, 1980.

Huyer, A., Hydrographic observations along the CODE central line off northern California, 1981, *J. Phys. Oceanogr., 14,* 1647–1658, 1984.

Leetmaa, A., D. W. Behringer, A. Huyer, R. L. Smith, and J. Toole, Hydrographic conditions in the eastern Pacific before, during and after El Niño, *Progr. Oceanogr.,* in press, 1987.

Mendo, J., L. Pizarro, and S. Castillo, Monthly upwelling and turbulence indices off the Peruvian coast at Callao and Trujillo during the period 1953–1983, in *The Anchoveta and Its Ecosystem—Three Decades of Change,* edited by D. Pauly and I. Psukayama, International Center for Living Aquatic Resource Management, Manila, in press, 1987.

Paluszkiewicz, T., and R. L. Smith, Subsurface current and temperature time series from the Peruvian continental shelf during El Niño 1982–1983, in *El Nino Atlas 1982–83,* edited by A. Leetmaa and J. Witte, Nova University, Dania, Fla., 1984.

Philander, S. G. H., and A. D. Siegel, Simulation of El Niño of 1982–1983, in *Coupled Ocean-Atmosphere Models,* edited by J. C. J. Nihoul, pp. 517–541, Elsevier, New York, 1985.

Roffer, C., and A. Leetmaa, CTD/02 data collected in November 1981 and March 1982 for EPOCS, *NOAA Tech. Memo. ERL AOML-52,* 123 pp., 1982.

Roffer, C., D. Behringer, and A. Leetmaa, Hydrographic data collected in 1982 and 1983 for EPOCS, *NOAA Tech. Memo. ERL AOML-57,* 259 pp., 1984.

Romea, R. D., and R. L. Smith, Further evidence for coastal trapped waves along the Peru coast, *J. Phys. Oceanogr., 13,* 1341–1356, 1983.

Smith, R. L., A comparison of the structure and availability of the flow field in three coastal upwelling regions: Oregon, northwest Africa, and Peru, in *Coastal Upwelling, Coastal and Estuarine Sci. Ser.,* vol. 1, edited by F. A. Richards, pp. 107–118, AGU, Washington, D. C., 1981.

Smith, R. L., Peru coastal currents during El Niño: 1976 and 1982, *Science, 221,* 1397–1399, 1983.

Thompson, R. O. R. Y., Continental-shelf-scale model of the Leeuwin Current, *J. Mar. Res.,* in press, 1987.

Wooster, W. S., and O. Guillen, Characteristics of El Niño in 1972, *J. Mar. Res., 32,* 387–404, 1974.

Wyrtki, K., El Niño–The dynamic response of the equatorial Pacific Ocean to atmospheric forcing, *J. Phys. Oceanogr., 5,* 572–584, 1975.

A. Huyer, T. Paluszkiewicz, and R. L. Smith, College of Oceanography, Oregon State University, Corvallis, OR 97331.

(Received April 6, 1987;
accepted April 20, 1987.)