ORIGIN OF PRODUCTIVITY ANOMALIES DURING THE 1982-83 EL NIÑO

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ABSTRACT

The biological changes of El Niño are clearly related to the sequence of physical changes in the marine environment. During years when there is no El Niño, a basinwide nutricline tilt set up by trade winds brings the nutricline to a favorable, shallow depth along the coast of Peru. During El Niño the nutricline is progressively depressed, so coastal upwelling transports reduced quantities of nutrients to the surface. Productivity of the coastal upwelling ecosystem during the 1982-83 El Niño was decreased fourfold to twentyfold by the reduced nutrient supply. The decrease of new primary production available to the food chain caused proportional reductions in the fish and seabirds.

RESUMEN

Los cambios biológicos vinculados con El Niño están claramente relacionados con la secuencia de cambios físicos en el ambiente marino. Durante años no-El Niño el declive de la nutriclina, a lo largo de la cuenca oceánica, condicionado por los vientos alisios, ubica a la nutriclina en una profundidad favorable, reducida, frente a las costas peruanas. Durante El Niño esta isolínea es progresivamente empujada hacia profundidades mayores, de manera tal que los afloramientos costeros aportan menos nutrientes a la superficie. La productividad de los ecosistemas de afloramientos costeros durante El Niño de 1982-83 se redujo en 4 a 20 veces debido al reducido aporte de nutrientes. La disminución de la producción primaria disponible para la cadena alimentaria provocó reducciones en los peces y en las aves marinas.

INTRODUCTION

The ocean off the west coast of South America is the most productive region of the world ocean; Buchanan (1886) reported, "No waters in the ocean so teem with life as those on the west coast of South America." Early in the twentieth century Coker (1918) associated cool ocean temperatures with the abundance of fish and seabirds (Coker 1908, 1919). Coker (1918) also correctly identified upwelling as the process responsible for persistent cool ocean temperatures in the tropical setting of the Peru coast, and he speculated that perhaps the greater solubility of gases in cooler seawater enabled the upwelled water to support more "growth of the minute plants that form the basis of the food supply of all the marine animals." Coker's speculation was surprisingly close to being correct; today we believe it is the abundance of available nitrogen and phosphorus in the cool, upwelled water that makes this region the world's richest (Ryther et al. 1971).

Accurate descriptions of El Niño and the changes in currents and rainfall that accompany it were published at the end of the nineteenth century by several Peruvian scholars such as Carranza (1892), Eguiguren (1894), and Pezet (1896). Murphy (1926) associated the decrease of plankton, collapse of local fisheries, and widespread death among seabirds in 1891 and 1925 with the sudden warming of the ocean off Peru. The common understanding was that upwelling failed during El Niño. To understand how El Niño affects the biota we must understand why the ocean off the west coast of South America is normally so fertile.

As Coker (1918) indicated, the process of coastal upwelling is responsible for the fertility of this region. Coastal upwelling is a circulation pattern that overrides both the nutrient limitation that characterizes permanently stratified waters, and the light limitation that characterizes deeply mixed waters. Coastal upwelling is set in motion by equatorward winds that transport water offshore, resulting in an equal volume of water flowing up close to the coast to replace the water moved offshore. The surface layer forced offshore by the equatorward winds is extremely shallow, on the order of ten to twenty meters deep. Subsurface water is brought to the surface and, once there, is transported horizontally away from the upwelling site in a coherent surface flow (Barber and Smith 1981). The waters of the ocean below the thermocline are rich in inorganic plant nutrients like nitrate, phosphate, and silicate; the subthermocline nutrient reservoir of the ocean is one of the major nutrient pools of the globe (Redfield 1958). Vertical transport of subsurface water injects new nutrients into the surface and forms a shallow, wind-driven, surface Ekman layer that is vertically stabilized by a density gradient, and provides optimal light conditions for plankton photosynthesis.

This sequence in upwelling of vertical transport followed by vertical stabilization is analogous to the seasonal mixing and stratification cycle occurring in
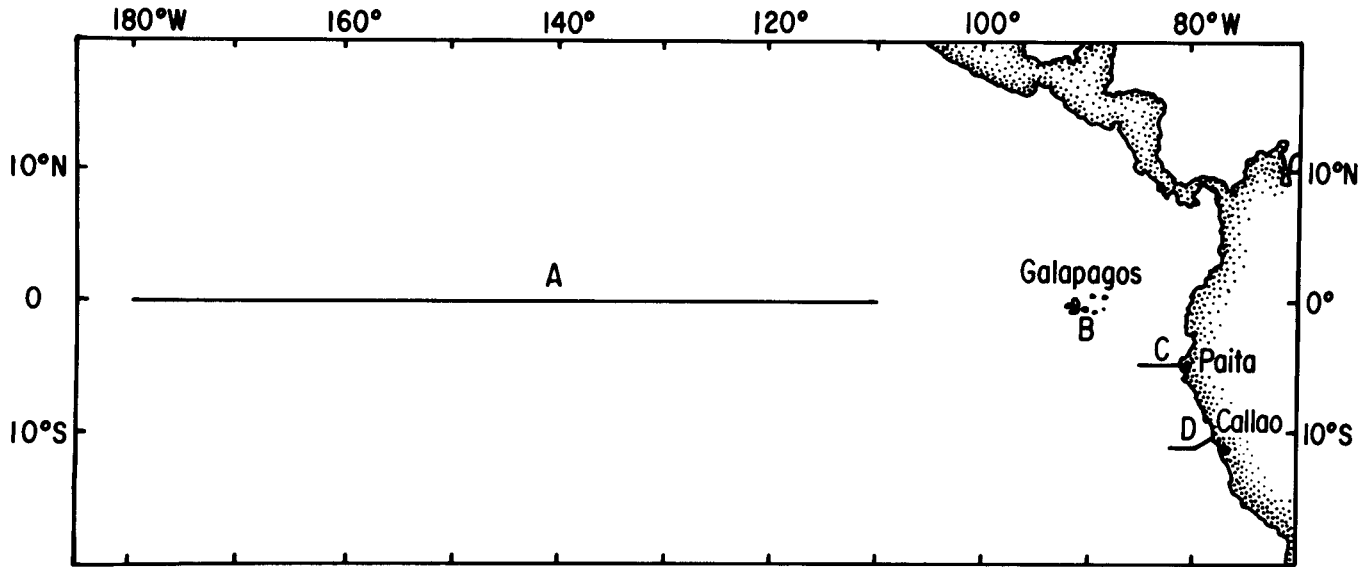
Figure 1. Chart of the central and eastern tropical Pacific showing the location of the transects and station described in this report: A, zonal section along the equator from 180°W to 110°W; B, Galápagos Islands time series station; C, Paita transect along 5°S from 85°W to the coast; D, 10°30'S transect from 82°W to the coast.

temperate and high-latitude waters. What is different about upwelling is that optimal juxtaposition of the two opposing processes continues as long as the equatorward winds blow, whereas in the "spring" bloom of temperate, high-latitude waters there are only a few episodes of optimal conditions each year. Time limits on productivity enhancement are removed by coastal upwelling as long as winds are favorable; thus the total annual supply of new organic material to the ecosystem is much greater, and food chain enhancement is greatly increased (Ryther 1969).

Coastal upwelling is a response of a particular area of the ocean to a large-scale wind pattern; implicit in the concept of a local response is the idea that the water upwelling to the surface layer is entrained from a relatively shallow depth of 40 to 80 meters. The gradient that separates the nutrient-rich subsurface waters from the nutrient-depleted surface waters is called the nutricline, just as the temperature gradient is called the thermocline. The thermocline and nutricline in the eastern portion of the Pacific (Figures 1 and 2) are much shallower than they are in midocean or in the west because of action of the large-scale winds on the ocean surface (Cane 1983; Rasmusson and Wallace 1983). Thus large-scale winds have two relatively separate connections to coastal upwelling: (1) they provide the local driving force for coastal upwelling, and (2) by setting up the large-scale thermocline and nutricline tilt, they determine the properties (temperature and nutrient content) of the water that can be entrained into the upwelling circulation when the local winds are favorable.

In describing the oceanographic processes involved in El Niño, Wooster and Guillen (1974) observed that warm water appeared and nutrients decreased during El Niño. Since cold water and high nutrients are signatures of coastal upwelling, it was widely assumed that upwelling weakened during El Niño. Analyses of coastal wind measurements in the last five years have indicated that in previous El Niño events (Enfield 1981) and in the 1982-83 El Niño (Smith 1983) the equatorward winds driving coastal upwelling did not weaken until late in the event's development. During the 1982-83 El Niño, observations indicated that upwelling continued as late as March 1983, but changes in temperature and nutrients between November 1982 and March 1983 showed that the water entrained by the upwelling circulation had an entirely different nutrient and temperature character. An explanation of this apparent contradiction is that as the thermocline and nutricline were progressively depressed below the depth where source water was entrained into the upwelling circulation (40 to 80 m), nutrient transport to the surface layer was reduced, and temperature increased.

The surprising conclusion we reach from these observations is that nutricline depression, not cessation of upwelling, was the process that decreased the nutrients and, in turn, caused primary production to decrease, eventually causing collapse of the upwelling food chain. A corollary of this conclusion is that it was collapse of the food chain, not direct thermal effects, that caused the biological anomalies during the 1982-83 El Niño.
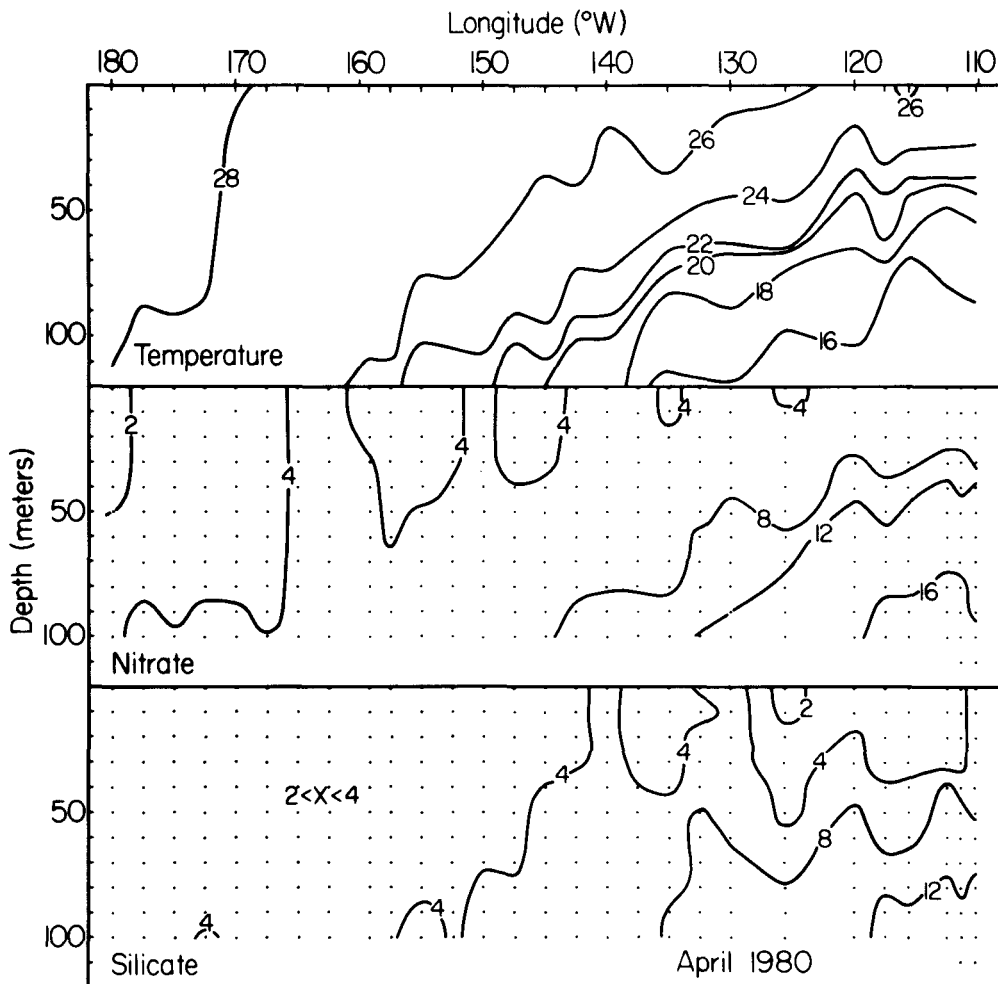
Figure 2. Zonal section along the equator from 110° to 180°W, showing temperature (°C), nitrate (μM), and silicate (μM) during April 1980. Temperature was measured as a continuous vertical record, and discrete nutrient measurements were made at the depths shown by the dots.

PROGRESSION OF THE 1982-83 EVENT

The 1982-83 El Niño began in August around the Galápagos Islands (Halpern et al. 1983), and in late September and October along the coast of Peru (Chavez et al. 1984). Figure 3 shows the change in surface and 60-m temperature at a shore station in the Galápagos Islands (Kogelschatz et al., in press). El Niño is well defined by both the surface and 60-m temperatures; in fact, the onset in September 1982 and recovery in June 1983 is more sharply delineated in the 60-m temperature signal. Another aspect of this time series is that an increase or decrease in surface temperature is always preceded by a change at 60 m; as has been noted previously (Enfield 1981; Barber and Chavez 1983), El Niño in the eastern Pacific is initially a subsurface (thermocline) anomaly that only secondarily reaches the surface.

The pattern of variation in nitrate (Figure 3) shows El Niño's large impact on nutrients in the eastern tropical Pacific. Surface-layer values at the beginning and end of the time series show that nitrate values of 2

to 6 μM are characteristic in this region. This is further supported by the large-scale zonal profile shown in Figure 2. The relationship between phytoplankton growth and ambient nutrient concentration is complex (Dugdale et al. 1981), but for a general understanding of El Niño's biological effects it is adequate to know that nitrate concentrations of 2 μM or higher constitute favorable nutrient conditions where the uptake-versus-concentration relationship is saturated. Figure 3 shows that, in the absence of El Niño, Galápagos waters are nutrient-rich; that is, there are saturating concentrations of nitrate in the surface layer most of the time.

The surface concentration of nitrate for six and one-half months during the 1982-83 El Niño, from December 1982 to mid-June 1983, was very low, often below the detection limit of 0.02 μM. Such concentrations are clearly nutrient-poor and will necessarily decrease the new production of organic matter by phytoplankton (Dugdale and Goering 1967). The silicate time series (not shown) indicates that this nutrient
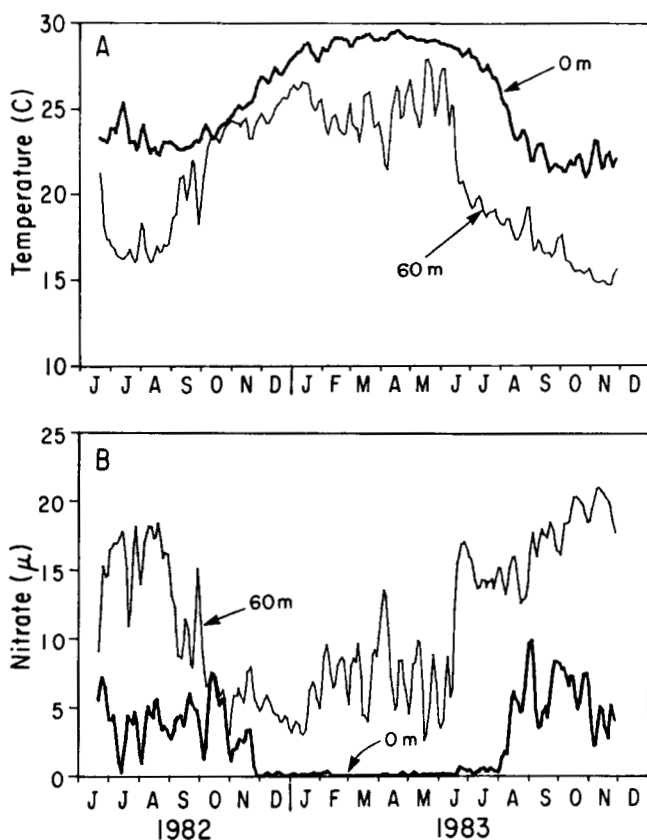
Figure 3. Time series plot of temperature and nitrate in Academy Bay, Galápagos Islands, at 0 m and 60 m during the 1982-83 El Niño.
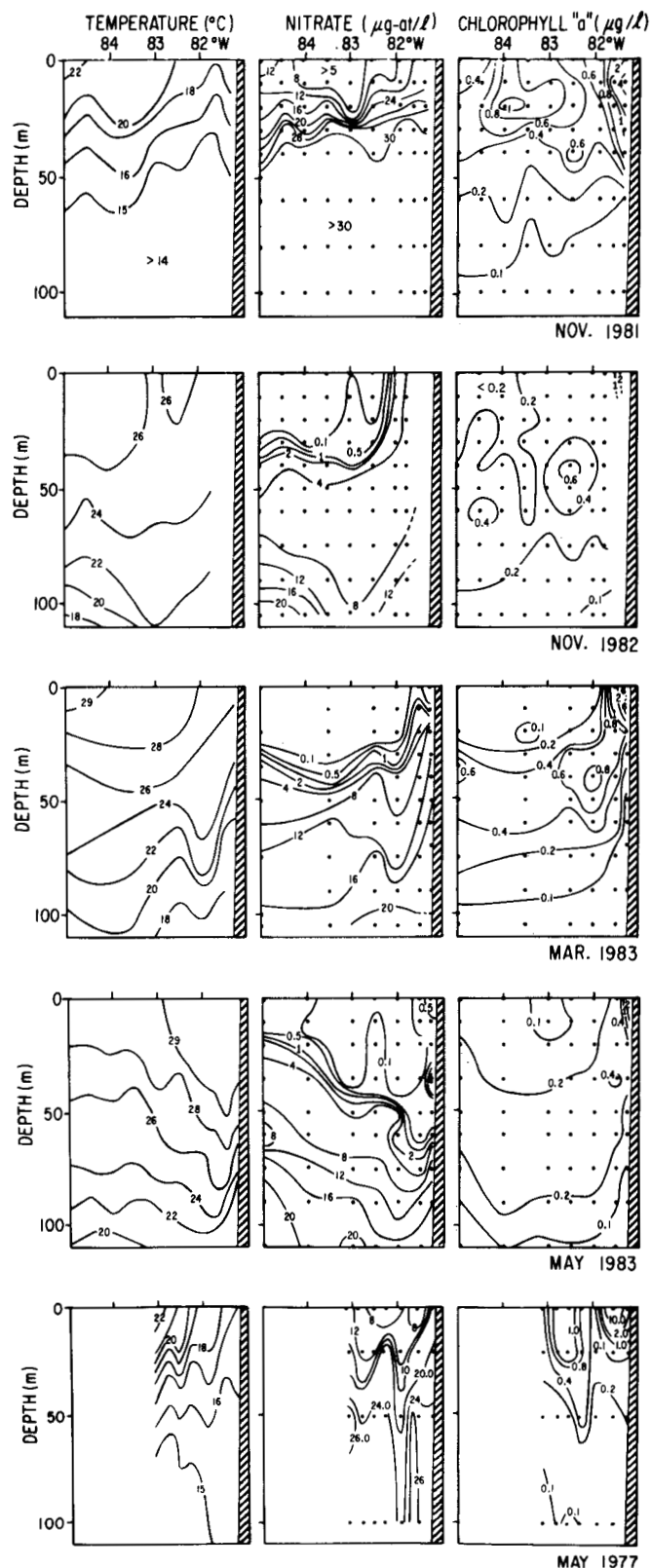

Figure 4. Cross-shelf profiles of temperature, nitrate, and chlorophyll a along a 5°S transect from 85°W to the coast. November 1981 shows normal conditions; November 1982 is during onset; March 1983 is during maturation; May 1983 is during the peak of the anomaly; May 1977 shows normal conditions.

covaried with nitrate at the surface and at 60 m, but unlike nitrate, it was never depleted in the surface layer. In the equatorial Pacific there is an atom ratio excess of silicate-silicon relative to nitrate-nitrogen; this is the reason we concentrate on nitrate in this description of nutrient conditions.

The two November 1982 sections at 5°S and 10°30'S off the coast of Peru (Figures 4 and 5) were during onset of El Niño, but the temperature anomaly had already reached 5°C. Evident in the November 1982 section is the characteristic thermocline and nutricline depression. The 20°C isotherm, which is the middle of the thermocline, is depressed over 100 meters close to the coast when compared to two sections made in November 1981 (Figures 4 and 5). Coastal upwelling driven by coastal winds continued in November 1982 to supply a band next to the coast with nutrients; this narrow zone of nutrient enrichment supported relatively high phytoplankton biomass.

Comparison of the SST along the 5°S transect during November 1982 and November 1983 (Figure 6) shows that the offshore-to-inshore temperature gradient is similar in magnitude even though the entire section is 5°C warmer during November 1982. The presence of the offshore-to-inshore gradient indicates
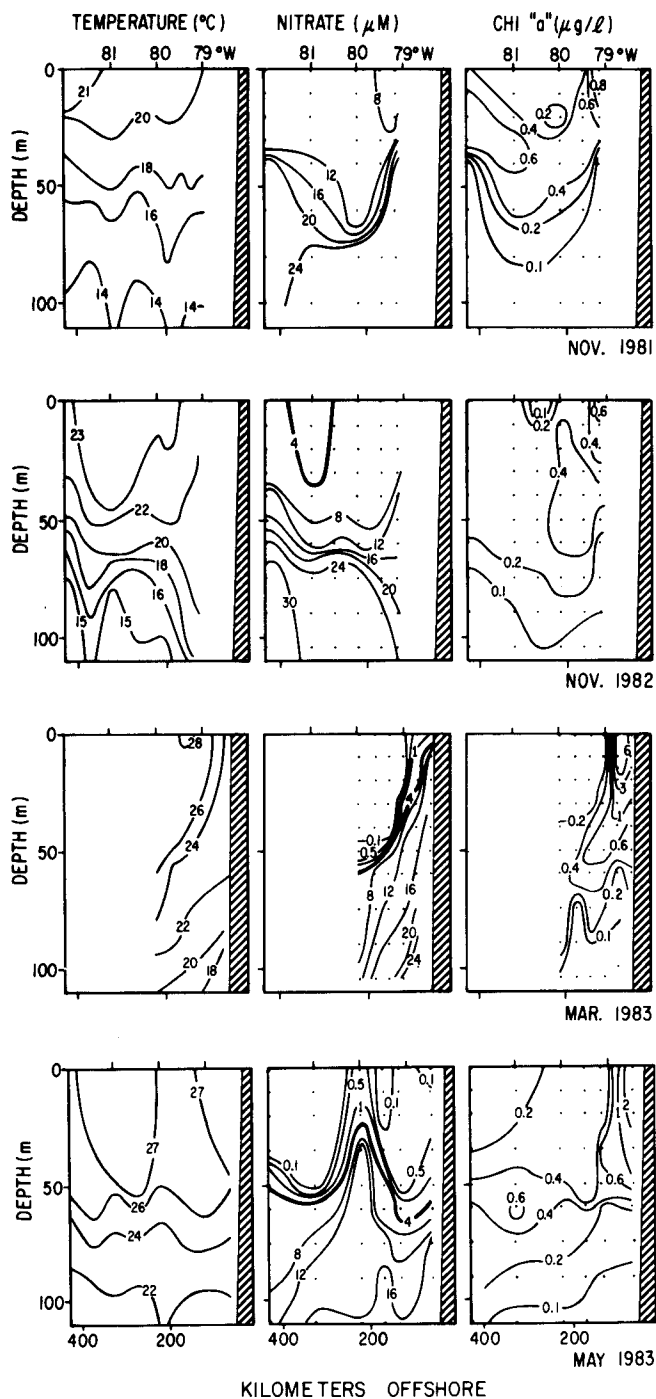
Figure 5. Cross-shelf profiles of temperature, nitrate, and chlorophyll *a* along 10°30'S from 82°W to the coast. November 1981 shows normal conditions; November 1982 is during onset; March 1983 is during maturation; May 1983 is during the peak of the anomaly.

extended only about 30 km out from the coast; after recovery in November 1983 it extended over 200 km from the coast. The primary productivity along the 5°S transect shows that an inshore productivity maximum was present in November 1982, but productivity integrated across the 5°S transect from the coast to 85°W was much reduced (Figure 6). The mean surface productivity along the transect during November 1982 was 51 mgC/m³/day, whereas during November 1983 the average was 192 mgC/m³/day, or 3.8 times higher.

Temperatures continued to increase as the 1982-83 event progressed into March 1983 (Figure 3); however, at the time of the March 1983 cruise the thermocline was slightly shallower along the 5°S and 10°30'S transects than it was during the onset phase (Figures 4 and 5). In March 1983, coastal upwelling continued, as shown by the upward tilt in the isotherms close to the coast and by the presence of the offshore-to-inshore temperature gradient of about 3°C (Figure 6). The narrow phytoplankton-rich band of water close to the coast is evident in the chlorophyll sections for March 1983, and the size of the area bounded by the 1 mg/m³ concentration remained reduced. High chlorophyll concentrations were still restricted to a 30-km-wide zone next to the coast, whereas during April 1984 the zone of the phytoplankton-rich water extended 400 km from the coast. By March 1983 the mean surface primary productivity along the 5°S transect was reduced to 27 mgC/m³/day, whereas during April 1984 the mean value was 245 mgC/m³/day, or 9.2 times higher than the El Niño condition.

May 1983 conditions show the maximum expression of the biological and physical anomalies of the 1982-83 El Niño. The SST anomalies reached 10°C, and the middle of the thermocline was depressed below 100 m (Figures 4 and 5). Temperature profiles made during May 1983 and May 1977 provide an interesting contrast. During May 1983 there is no evidence of coastal upwelling; on the contrary, the isotherms tilt downward toward the coast. During May 1977, upward tilt typical of coastal upwelling is very evident. In May 1983 there is no longer an offshore-to-inshore SST gradient; on the contrary, the inshore waters are slightly warmer (Figure 6). The chlorophyll field for May 1983 shows that the normally rich coastal ocean has become relatively barren. However, the July 1983 results shown in Figure 6 show the rapid phytoplankton recovery that occurred in the nearshore zone all along the coast of Peru. After extremely low primary productivity in May 1983, phytoplankton production rapidly reestablished in mid-July 1983, and the coastal waters returned to their normally productive condition. During May 1983, the mean surface primary productivity along 5°S had
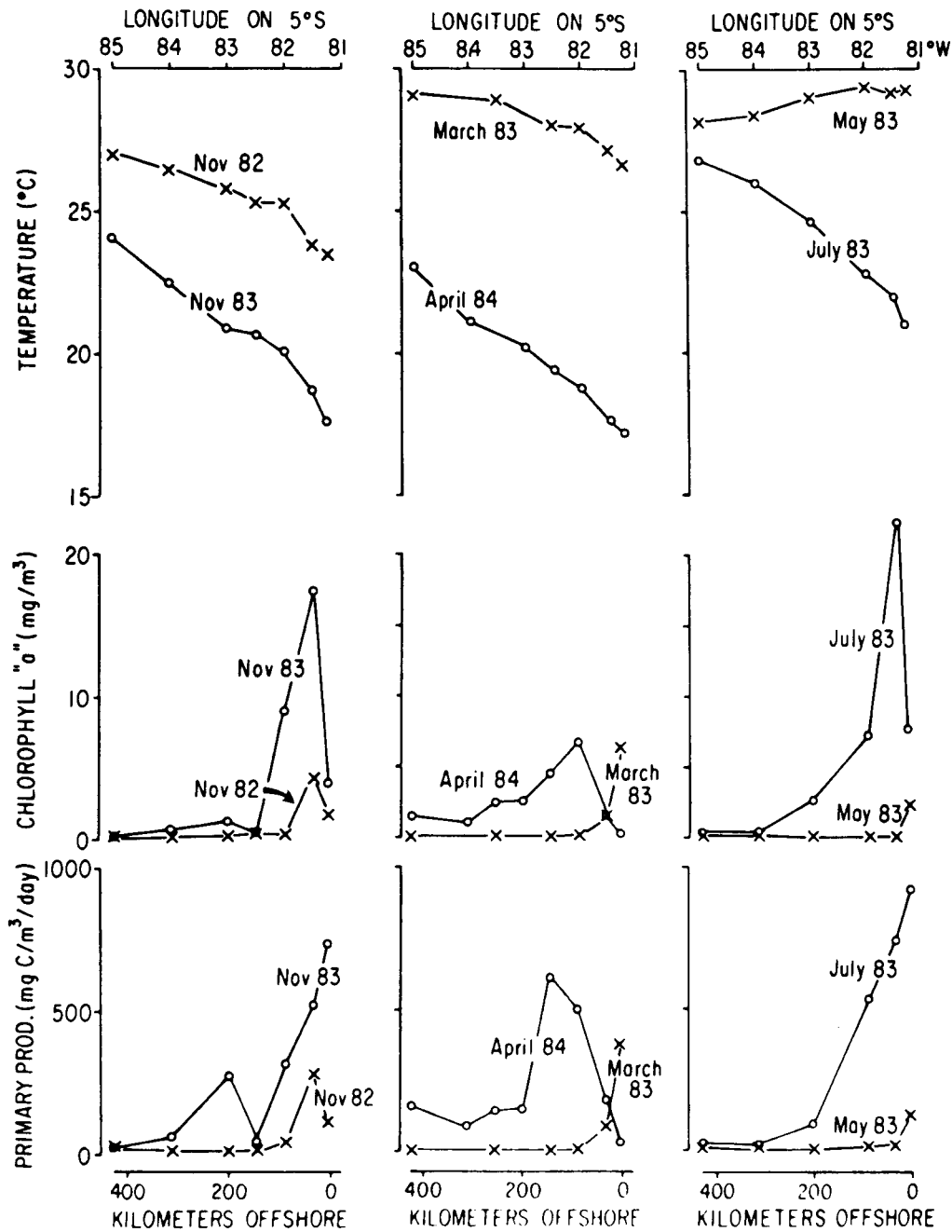
that upwelling continued close to the coast despite the 5°C warm anomaly present throughout the water column. The concentrations of chlorophyll along the 5°S transect during November 1982 and November 1983 (Figure 6) show that during onset in 1982, the phytoplankton-rich band, as shown by the 1 mg/m³ contour,

Figure 6. Comparison of surface temperature, chlorophyll a, and primary productivity along the Paita transect from 85°W to the coast.

dropped to its lowest value—10 mgC/m³/day—whereas during July 1983 it increased to 219 mgC/m³/day, a value 21.9 times higher than the El Niño condition. At the peak of the anomaly primary production was reduced to 5% of the normal quantity.

We believe this dramatic decrease in the supply of phytoplankton productivity was the primary cause of the widespread reproductive failures and adult mortalities (Barber and Chavez 1983) that were observed in fish, birds, and marine mammals during the 1982-83 El Niño.

ACKNOWLEDGMENTS

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