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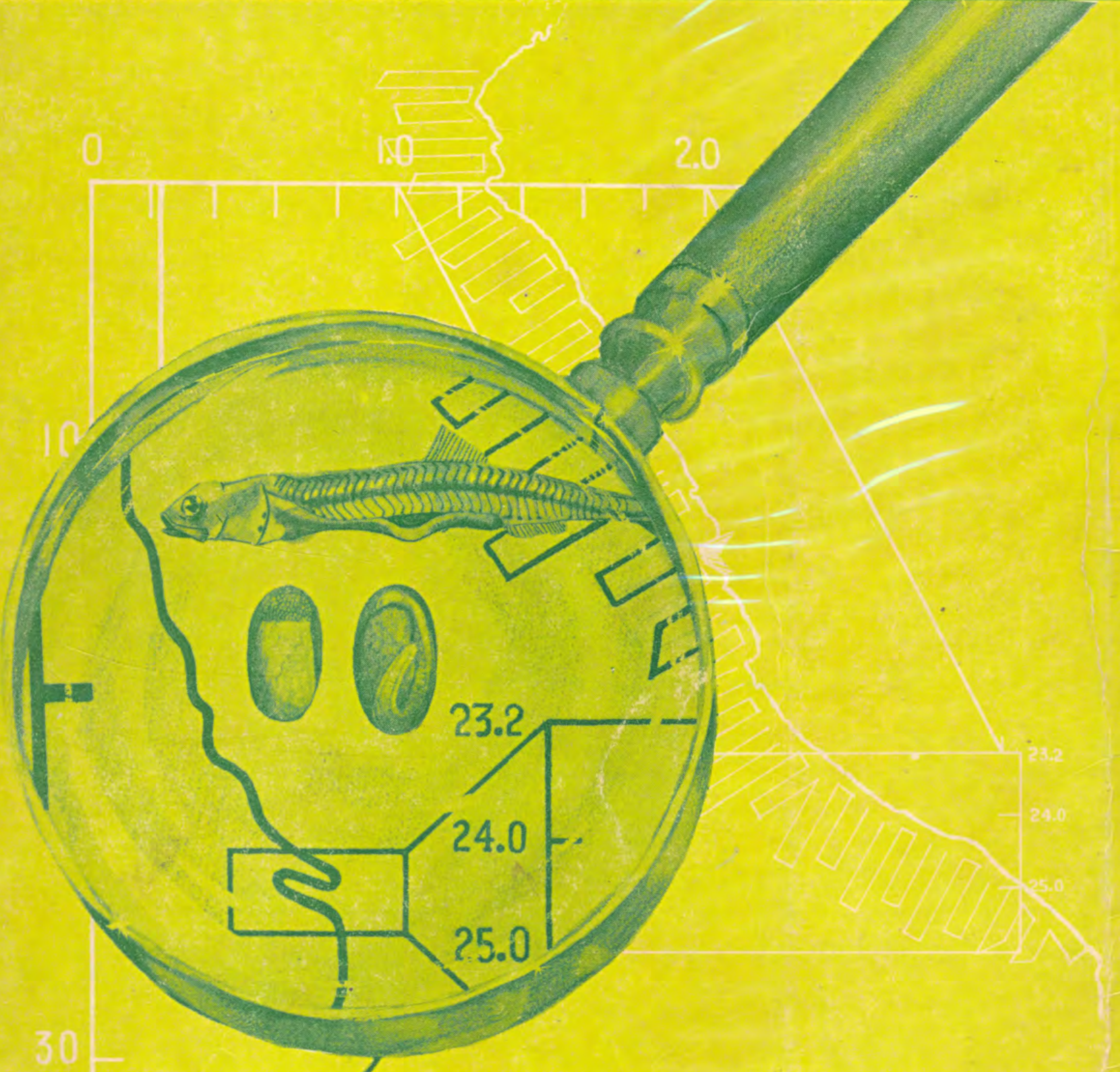

INVESTIGACION COOPERATIVA DE LA ANCHOVETA Y SU ECOSISTEMA -ICANE- ENTRE PERU Y CANADA

CALLAO 1981 PERU

ON THE POSSIBLE ENHANCEMENT OF OXYGEN DEPLETION IN THE COASTAL WATERS OF PERU BETWEEN 6ºS AND 11ºS +

by

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ABSTRACT

A precarious balance exists between oxygen consumption and supply in the deeper water over the continental shelf of northern Peru. Because consumption of oxygen by oxidation of organic matter produced in the euphotic zone exceeds the supply of oxygen brought onto the shelf by upwelling, depletion of the **in situ** concentrarion of oxygen occurs. Using a two layer, steady-state circulation, the estimated rates of consumption and supply of oxygen over the shelf between two transects are approximately equal. The rate of **in situ** depletion of oxygen exceeds the rate of addition of oxygen by upwelling of relatively oxygen-rich water. In the model, the volume of oxygen-depleted water increases to the south, consistent with observations.

RESUMEN

El balance entre el suministro y el consumo de oxígeno es precario en las aguas profundas sobre la plataforma continental en el norte del Perú. El agotamiento de la concentración de oxígeno **in situ** se da porque el consumo por oxidación de la materia orgánica en la zona eufótica es mayor que el suministro por afloramiento en la plataforma. Las tasas de consumo y suministro de oxígeno en la plataforma entre dos líneas de crucero son aproximadamente iguales, cuando las estimaciones se hacen asumiendo una circulación estable de dos capas. La tasa de agotamiento de oxígeno **in situ** excede la de aumento por afloramiento de aguas relativamente ricas en oxígeno. En el modelo el volumen de agua con agotamiento de oxígeno aumenta hacia el sur, lo cual es consistente con las observaciones.

INTRODUCTION

The remarkable productivity of the coastal waters of Peru in terms of phytoplankton and fish is well known. (c.f. RYTHER et al., 1971 and ROJAS DE MENDIOLA, 1971). A general description of the circulation off the coast of Peru has emerged from several major surveys. WYRTKI (1963) postulated a predominantly equatorward surface flow in two distinct currents. Offshore, the Peru Current is part of the anticyclonic subtropical gyre of the South Pacific. Nearshore, the surface flow is still equatorward, but confined to a very shallow wind-drift layer. Poleward flow occurs beneath the surface currents in the Peru-Chile Undercurrent and the Peru Countercurrent (WOOSTER and GILMARTIN, 1961). WOOSTER and GILMARTIN suggest that the undercurrent originates off northern Peru near 5°S. The undercurrent rises up onto the continental shelf leading to predominantly poleward flow on the shelf, even over the wide shelf north of 12°S. However, the circulation at 15°S is quite variable with complete reversals in the direction of flow observed from moored current meters (SMITH et al., 1971, and BRINK, ALLEN, and SMITH, 1978). Unlike other coastal upwelling regions, the Peruvian coast is characterized by shallow upwelling from depths less than 100 m (WYRTKI, 1963).

The coastal waters of Peru are known to have low subsurface concentrations of oxygen associated with high concentrations of nitrite (WOOSTER et al., 1975). In a section approximately 150 km off the coast, WOOSTER et al. (1975) observed increasing concentrations of nitrate to the south from 0 µg-at l^{-1} at 6°S to 4.5 µg-at l^{-1} at 17°S within the oxygen minimun layer, where the concentration of oxygen was less than 0.2 ml O_2 l^{-1}. DUGDALE et al. (1977) discuss this pattern as the result of coherent downstream processes within the undercurrent causing the sequence from north to south of the generation of nitrite from the reduction of nitrate within the oxygen minimum layer. In 1976, near 15°S, complete denitrification occurred in a layer contained within the undercurrent. DUGDALE et al. (1977) suggest that current reversals may have upset the normally precarious balance betweenn oxygen supply and utilization in the undercurrent by allowing oxygen-depleted water to return under regions of high productivity to suffer further reduction of nitrate and nitrite.

During a study of the dynamics of anchovy larvae conducted over the widest portion of the Peruvian continental shelf (6°S to 11°S) in November, 1977, we sampled two transects and some additional stations to examine the spatial variability of physical, chemical and biological properties and the suggestion of DUGDALE et al. (1977) that coherent processes in the circulation over the shelf may control the evolution of these fields. We shall describe the data from the transects and, using a steady-state two layer model of shallow Ekman-driven upwelling, we shall estimate an oxygen budget and suggest possible consequences for the distribution of inorganic nutrients over the continental shelf. We believe that DUGDALE et al. (1977) are correct when they describe a precarious balance between oxygen supply and use within the deeper flow and that such a balance is an usual situation arising from the large plant biomass found on the wide continental shelf off northern Peru, the shallowness of upwelling, and the southward flow of the deep layer over the shelf. There were no indications of any anomalous events during November, 1977; it was a normal November for coastal Peru.

METHODS

Stations along two transects, one beginning nearshore off Punta Chao (Station 71 at 8°30.S, 78°48'W) and another beginning offshore from Punta Culebras (Station 308 at 11°03.S, 79°44'W), were occupied on 5-7 November, 1977 and 28-30 November, 1977, respectively (Fig. 1, DOE, 1978). The northern boundary for this study is represented by two stations occupied on 3 November, 1977 (Station 55 at 5°14'S, 81°21'W and Station 56 at 6°47'S, 80°29'W) and one station occupied on 4 December, 1977 (Station 336 at 5°46'S, 81°01'W). Temperature and salinity observations were made using a Guildline 8705 digital conductivity, temperature, and depth probe (CTD) with a 500 decibar pressure sensor and an accuracy of 0.005°C in temperature and 0.005°/oo in salinity. Salinity samples taken for calibration with each CTD cast showed negligible instrument drift during the cruise. On the Punta Chao transect, water samples were collected using a rosette sampler associated with the CTD; on the Punta Culebras transect, water samples were obtained from a hydrocast after each CTD cast.

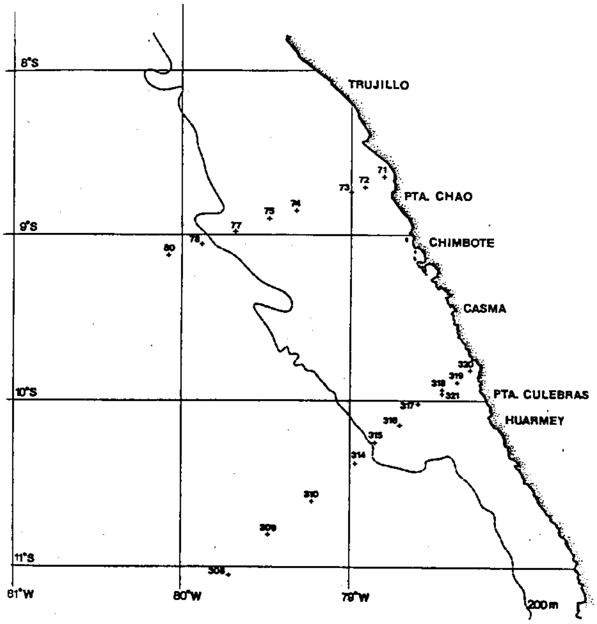


Fig. 1: Location of stations of transects off Pta. Chao, 5–7 November, 1977 and off Pta. Culebras, 28–30 November, 1977.

Dissolved oxygen in the water samples was determined by the Winkler method (STRICKLAND and PARSONS, 1968) with an uncertainty of 0.2 ml O_2 l^{-1} at oxygen concentrarions below 0.5 ml O_2 l^{-1}. Concentrations of all nutrients except nitrite were determined at sea using a Technicon AAII autoanalyzer and the methods of STRICKLAND and PARSONS (1968) and SLAWYK and MACISAAC (1972). Nitrite samples were frozen and analyzed ashore using the same instrument and methods. Freezing may cause a decrease in the concentration of nitrite and these data were used as indicators of trends only. Chlorophyll **a** and phaeophytin **a** were measured from a 25 ml sample. according to the method of LORENZEN (1966). Some filters awaiting analysis for plant pigments were frozen.

OBSERVATIONS

Hydrography

The hydrographic features of the transects were typical of the oceanographic conditions usually encountered off the coast of Peru (ZUTA **et al.**, 1978). Both sections (Figs. 2A and 2B) showed the isotherms sloping upward towards the

Fig. 2: Distribution of temperature (°C), salinity (°/oo) and oxygen (ml O^2 l^{-1}) off Pta. Chao (A, C, E) and off Pta. Culebras (B, D, F).

Fig. 2A

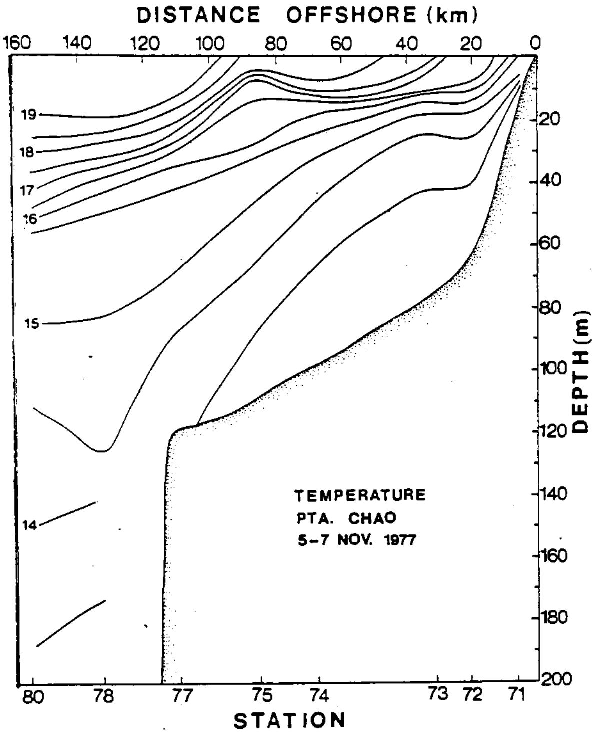


Fig. 2C

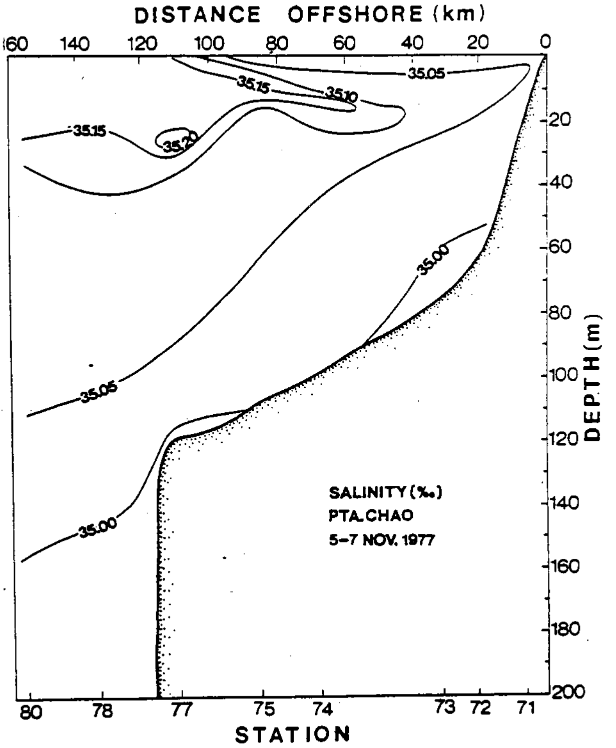


Fig. 2B

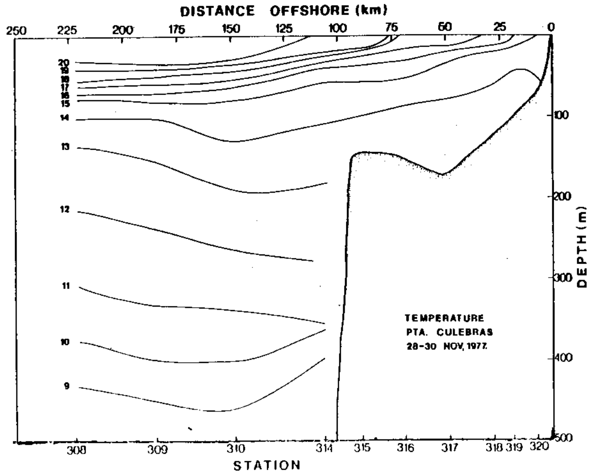


Fig. 2D

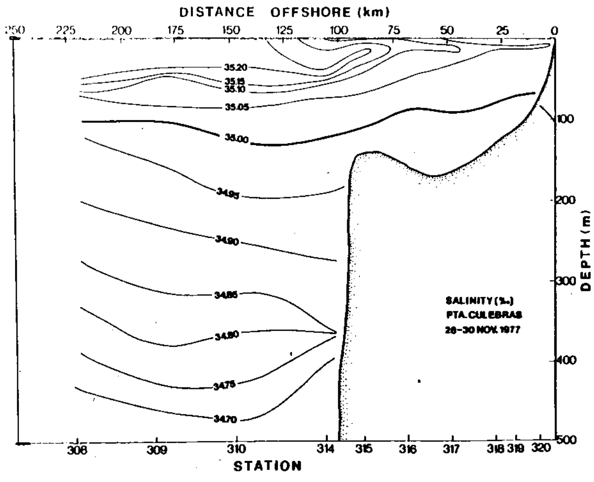


Fig. 2E

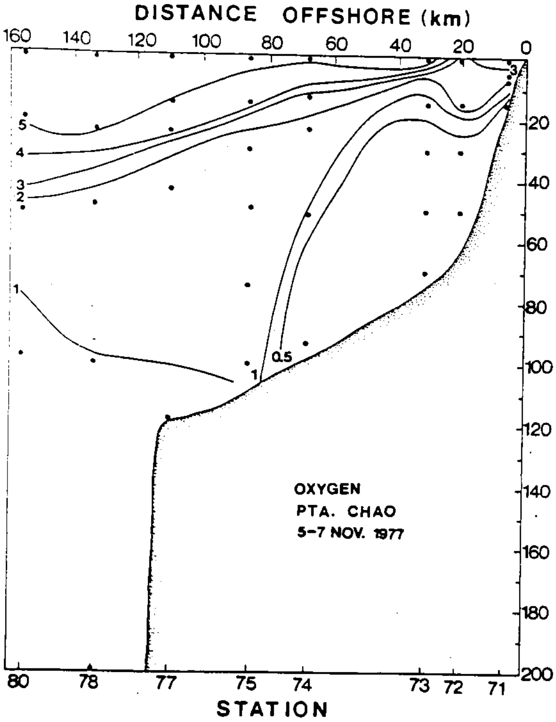
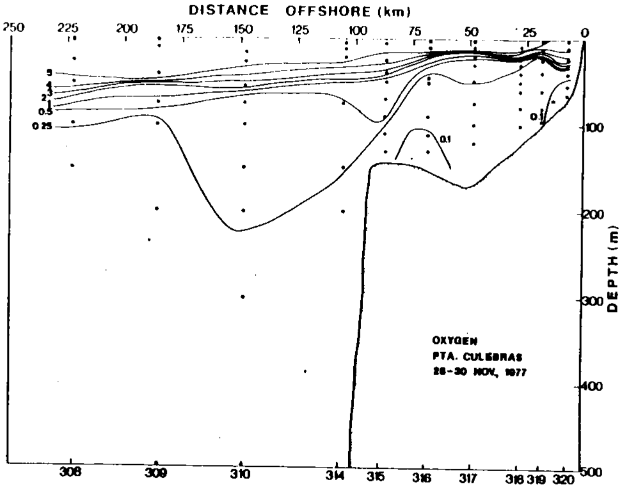


Fig. 2F



coast, a feature indicative of upwelling. Temperature can be used as an indicator of the behavior of the density field since density (σ_t) and temperature are correlated and temperature largely determines the density over the shelf where salinity variations are small, shown in Figures 2C and 2D. The lowest sea surface temperatures occurred adjacent to the coast and were 15.5°C for the northern transect at Pta. Chao and 15°C for the southern transect at Pta. Culebras. The offshore depth of these isotherms was less than 80 m suggesting shallow upwelling. The coldest water (13.7°C) over the shelf was observed near the bottom on both transects. This colder, deeper water was trapped on the shelf in the Pta. Chao transect.

Water with low concentrations of oxygen was encountered over the shelf on both transects (Figs. 2E and 2F). Off Pta. Chao concentrations of oxygen less than 0.5 ml O_2 l^{-1} occurred from midwater to bottom over the inner portion of the shelf, while off Pta. Culebras, water with less than 0.5 ml O_2 l^{-1} was observed below 30 m over most of the shelf and below 75 m over the slope. The two samples nearest the bottom adjacent to the coast on the Pta. Culebras transect and the bottom sample nearshore on the Pta. Chao transect had no detectable dissolved oxygen and the odor of hidrogen sulfide (H_2S) was obvious in the bottles. Except near the coast, the 16°C isotherm in the thermocline was correlated with the 2 ml O_2 l^{-1} isopleth for both transects.

Nutrients

The highest concentrations of phosphate, in excess of 3.0 μg-at l^{-1}, were observed inshore near the bottom over the shelf on both the Pta. Chao and Pta. Culebras transects (Figs. 3A and 3B). Lowest concentrations of phosphate, less than 1 μg-at l^{-1}, occurred in the euphotic zone of both transects with lower near surface phosphate levels

Fig. 3: Distribution of phosphate, silicate, nitrate plus nitrite, nitrite and ammonia in μg–at l^{-1} off Pta. Chao (A, C, E, G, I) and off Pta. Culebras (B, D, F, H, J).

Fig. 3A

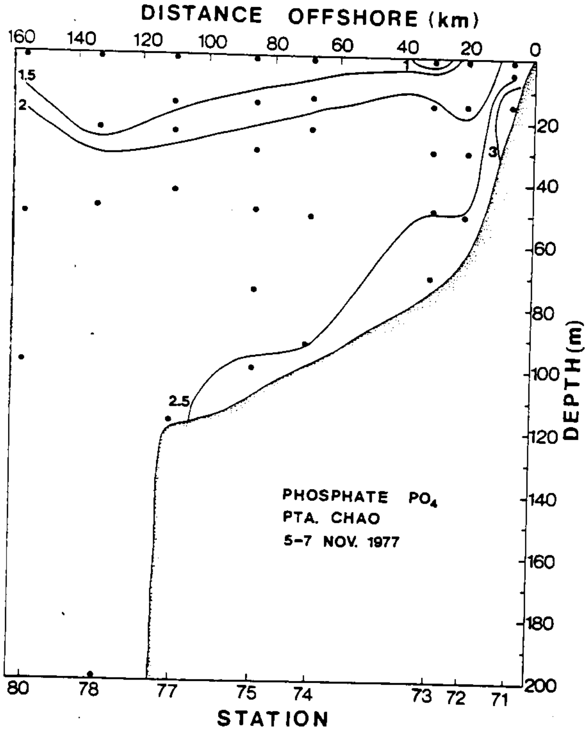


Fig. 3B

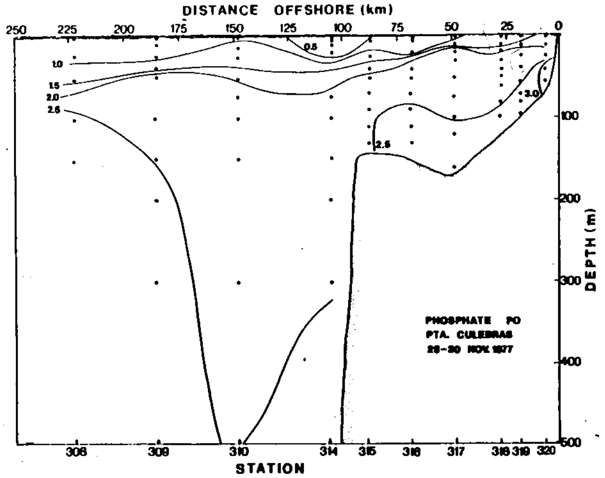


Fig. 3C

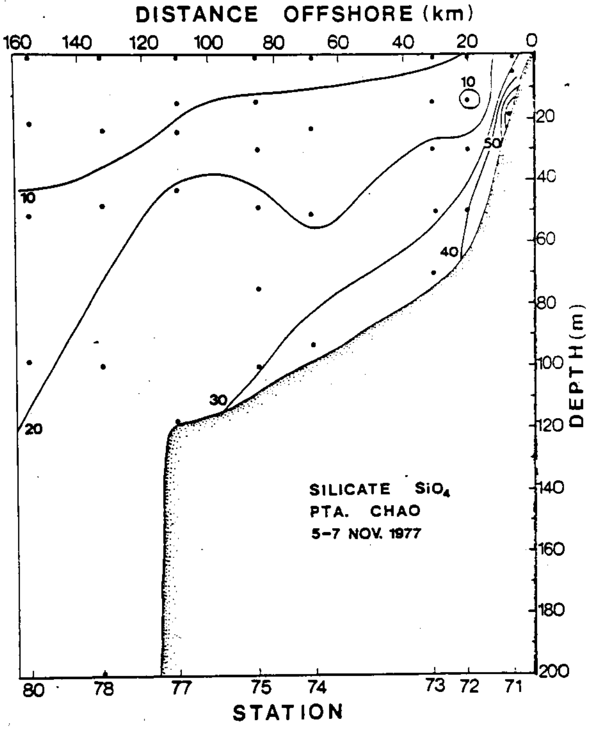


Fig. 3D

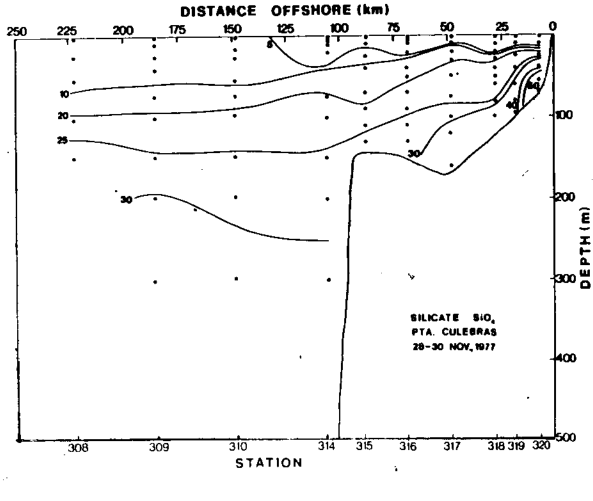


Fig. 3E

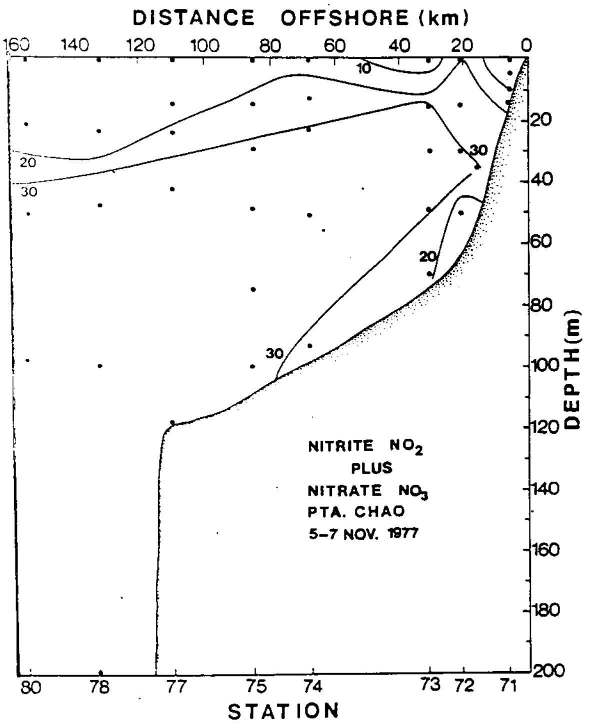


Fig. 3F

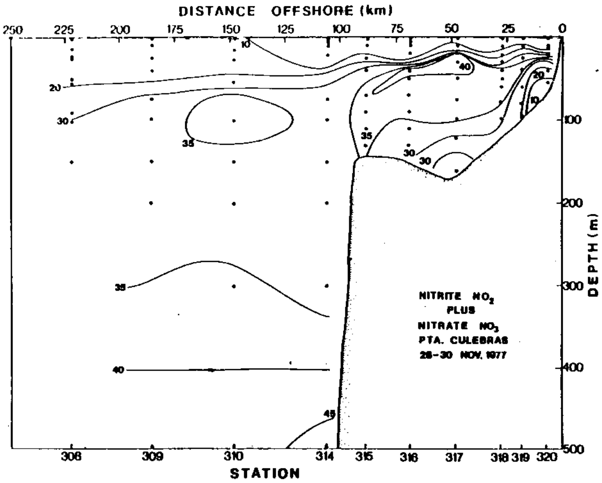


Fig. 3G

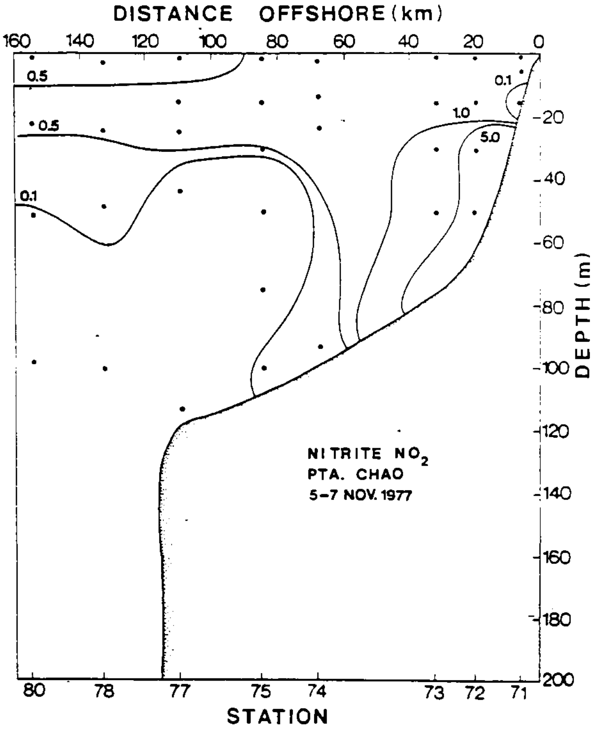
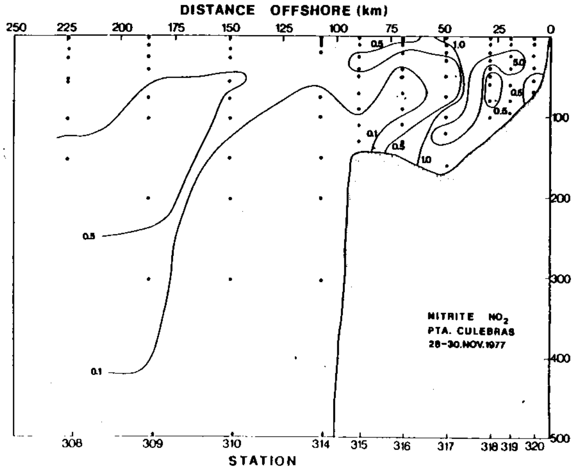


Fig. 3H



offshore at Pta. Culebras than at Pta. Chao. Distributions of silicate in the two transects (3C and 3D) were similar to those of phosphate with concentrations of silicate, exceeding 50 μg-at l^{-1}, occurring near the bottom at the most inshore station. Surface waters off Pta. Culebras has less silicate than surface waters off Pta. Chao, with the lowest values occurring in the euphotic zone.

Concentrations of nitrate-plus-nitrite were less than 10 μg-at l^{-1} in the euphotic zone and zero in the bottom two samples at the most nearshore station of both transects (Figs. 3E and 3F). Over the shelf, a mid-depth maximum of nitrate-plus-nitrite occurred for both transects, while the highest concentrations, greater than 35 μg-at l^{-1}, were at the greatest observation depths over the

Fig. 3I

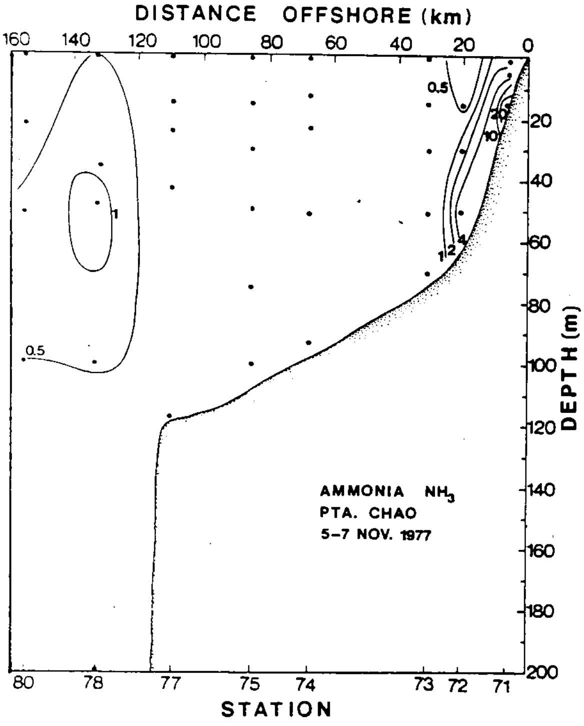
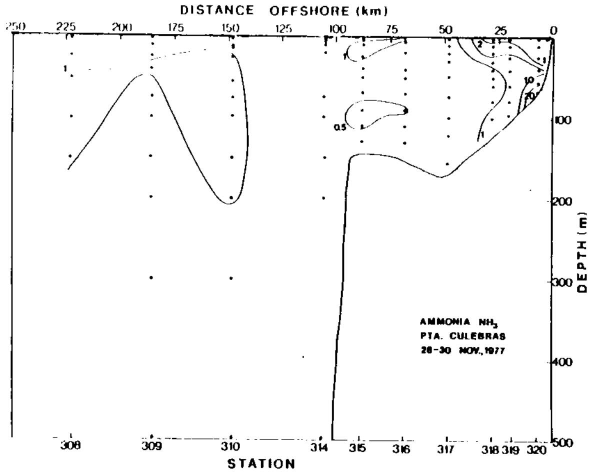


Fig. 3 J



slope. A nitrite maximum with concentrations greater than 5 μg-at l^{-1} occurred nearshore near the bottom on the Pta. Chao transect (Fig. 3G) while that concentration was observed at mid-depth nearshore off Pta. Culebras (Fig. 3H). Ammonia concentrations were greater than 20 μg-at l^{-1} near the bottom inshore on both transects (Figs. 3I and 3J). Concentrations of ammonia in excess of 1 μg-at l^{-1} throughout the water column were observed 5 km offshore at Pta. Chao and at 6 and 18 km offshore at Pta. Culebras. Total dissolved nitrogen, indicated by the sum of nitrate, nitrite, and ammonia, had a subsurface maximum with lowest concentrations in the Pta. Culebras. Total dissolved nitrogen as indicated by the sum of nitrate, nitrite, and ammonia had a subsurface maximum with lowest concentrations in the euphotic zone (less than 10 μg-at l^{-1}) and near the bottom (approximately 20 μg-at l^{-1}). Nitrite can result from bacterial reduction of nitrate or from oxidation of ammonia. In anoxic waters, hydrogen sulfide is not produced by bacteria decomposing organic material until nitrate and nitrite have been depleted as sources of electrons for the oxidation reactions. The presence of H_2S and the decrease in total dissolved nitrogen suggested that denitrification occurred near the bottom adjacent to the coast.

Phytoplankton

Concentrations of chlorophyll a exceeded 5 μg l^{-1} nearshore off Pta. Chao and exceeded 1 μg l^{-1} in the upper 20 m over much of the shelf (Fig. 4A). Off Pta. Culebras chlorophyll a never exceeded 5 μg l^{-1} and was generally between 0.5 μg l^{-1} and 1 μg l^{-1} in the upper 20 m over the shelf (Fig. 4B). Phaeophytin a on the Pta. Chao transect was greater than 0.5 μg l^{-1} throughout the water column over the inner half of the shelf

Fig. 4: Distribution of chorophyll a and phaeophytin a in μg l^{-1} off Pta. Chao (A, C) and off Pta. Culebras (B, D).

Fig. 4A

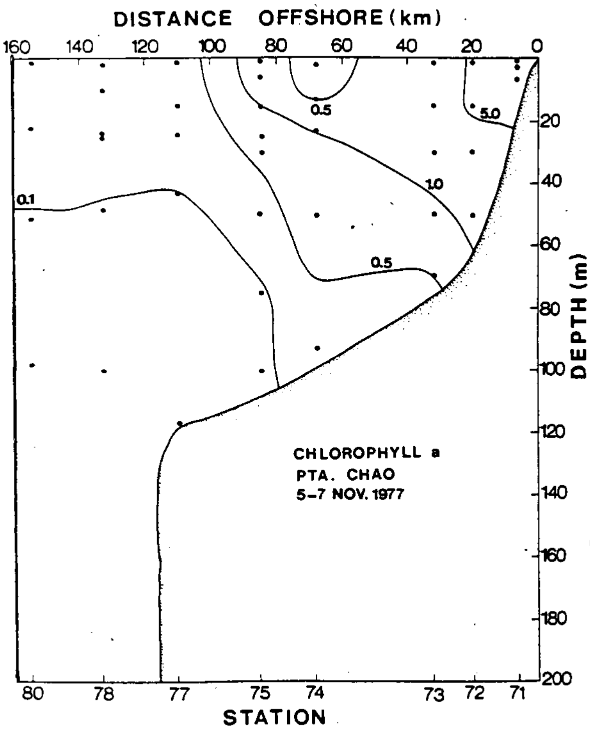


Fig. 4C

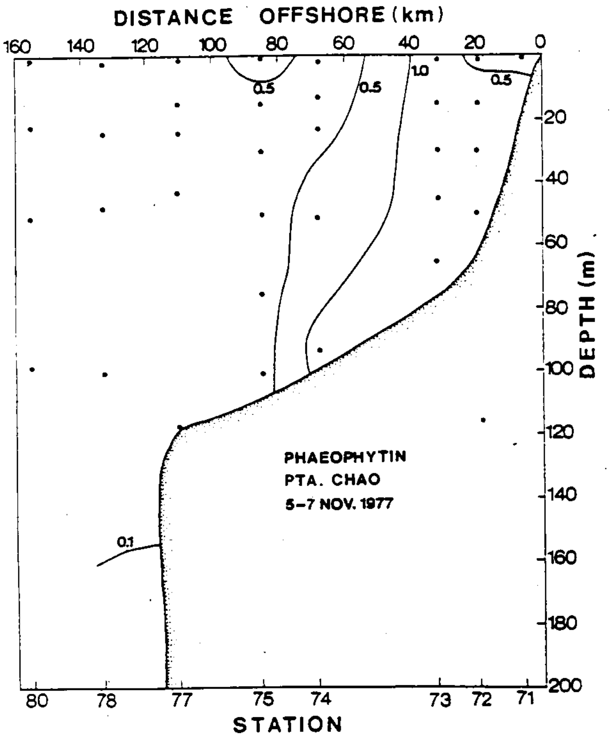


Fig. 4B

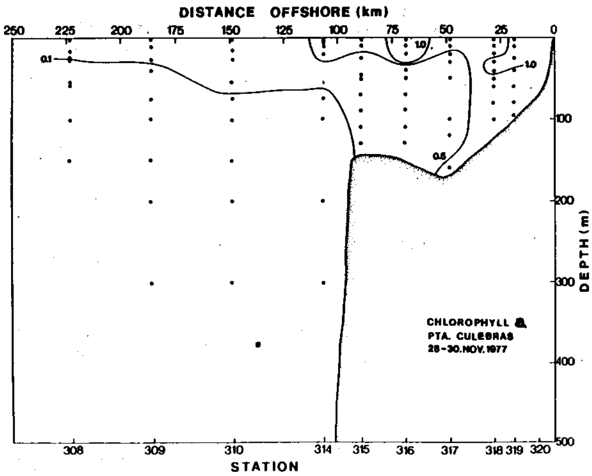
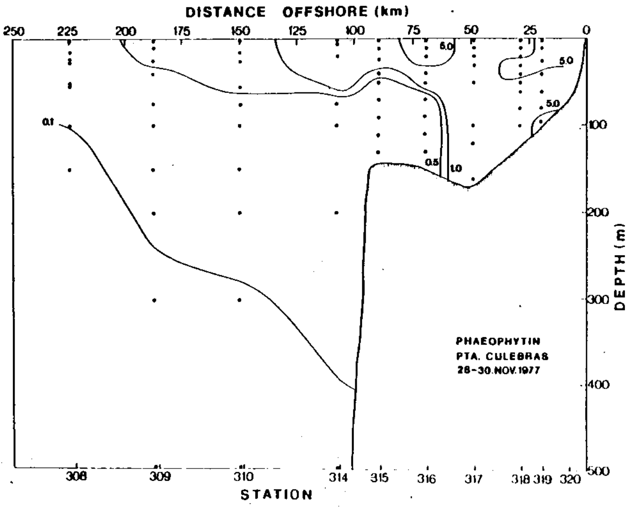


Fig. 4D



and less than 0.5 $\mu g\ l^{-1}$ throughout the water column elsewhere (Fig. 4C). On the Pta. Culebras transect, phaeophytin a was in excess of 1 $\mu g\ l^{-1}$ throughout the water column over the inner two-thirds of the shelf with regions exceeding 5 $\mu g\ l^{-1}$ (Fig. 4D). The 0.5 $\mu g\ l^{-1}$ isopleth of phaeophytin a off Pta. Culebras appeared at the outer portion of the shelf extending to 200 km offshore at approximately 50 m depth.

Summary

Several nearshore features were present in both transects: the bottom of the water column had high concentrations of phosphate, silicate, and ammonia, low concentrations of oxygen and detectable hydrogen sulfide cline (16°C isotherm) and by strong gradients of oxygen and nutrients across the base of the thermocline and euphotic zone. The Pta. Chao transect, the northern section, had higher chlorophyll a concentrations with a larger volume of water containing high chlorophyll a levels (greater than 0.5 $\mu g\ l^{-1}$) than the Pta. Culebras transect. The southern transect had a larger volume of water containing high concentrations of nitrite (greater than 0.5 $\mu g\ l^{-1}$) than the Pta. Chao transect. Furthermore, the Pta. Culebras transect had a larger volume of oxygen-poor water (less than 0.5 ml $O_2\ l^{-1}$) than the northern section.

Because of the strong on-offshore variations of the nutrients in the section data, it was difficult to use isolated stations to further explore alongshore variations. However, three stations between 5 and 7°S near Pta. Falsa, north of the transects of Fig. 1 which were of particular interest. Pta. Falsa is the westernmost projection of Peru into the Pacific Ocean where the continental shelf is extremely narrow. The two stations north of the cape (Stations 55 and 336) were very different from stations south of the cape. North of Pta. Falsa, the concentrations of chlorophyll a and phaeophytin a were low compared with Station 56 just south of the cape (Table 1). Concentrations of oxygen were greater than 1 ml $O_2\ l^{-1}$ north of Pta. Falsa, while to the south oxygen was depleted, at least nearshore below 30 m. The nitrate-plus-nitrite profiles were similar, with no evidence of denitrification occurring at these three northernmost stations.

Table 1: Data for stations north and south of Punta Falsa

	Depth (m)	Oxygen (ml $O_2\ l^{-1}$)	NO_3 + NO_2 (μg-at l^{-1})	Chl a ($\mu g\ l^{-1}$)	Phaeo a ($\mu g\ l^{-1}$)
	1	4.54	14.54	1.18	0.32
Sta. 55	6	4.55	14.40	1.09	0.29
5°14'S	18	3.62	20.16	1.09	0.45
81°21'W	30	2.91	25.91	1.16	0.28
139 m	50	2.17	29.57	0.68	0.32
	75	1.84	33.73	0.55	0.39
	100	1.36	36.04	0.51	0.41
Sta. 336	1	2.97	23.99	1.74	1.63
5°46'S	3	2.74	23.97	2.11	1.10
81°01'W	7	2.74	23.74	1.94	1.71
35 m	12	2.67	23.20	2.22	1.33
	24	1.83	26.02	1.50	2.31
	30	1.47	27.74	1.13	2.39
Sta. 56	1	5.63	13.48	6.99	6.51
6°47'S	6	5.55	10.08	5.44	2.31
80°29'W	18	0.87	31.79	10.62	10.77
49 m	30	0.14	35.25	11.19	6.84
	40	0.21	34.71	9.32	3.08

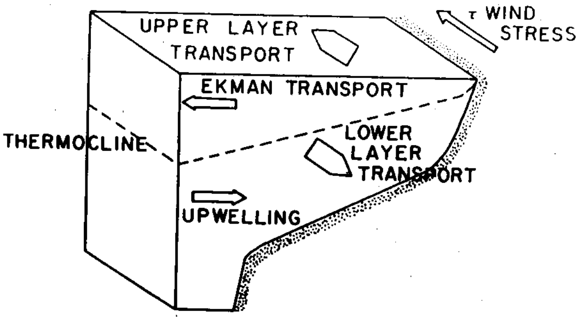
DISCUSSION

Circulation and the Oxygen Budget

Observations of circulation during the cruise are limited. However, combining these data with measurements from the Coastal Upwelling Ecosystems Analysis program (CUEA) reported by BRINK, SMITH, and HALPERN (1978), a picture of the circulation can be created. Moored current meter measurements during JOINT-II of CUEA show much less variability in the currents at 10°S than at 15°S. At 10°S (mooring PEYOTE), the mean alongshore flow is 20 cm s^{-1} southward below 30 m and is much greater than the 6 cm s^{-1} rms fluctuations. Farther to the south at 15°S (the C-line), where most of the CUEA measurements were made, the equatorward and offshore mean flow is confined to a shallow, less than 30 m, layer with an approximate two-dimensional mass balance at mid-shelf. The onshore transport is approximately equal to the predicted offshore Ekman transport $\tau\ (\rho f)^{-1}$, where τ is the wind stress, ρ is the density and f is the Coriolis frequency. In our data the geostrophic shear calculated from the density field is positive, with approximately equal relative transport below the thermocline for each transect. Using a lowered current meter at Sta. 314 on the southern transect to fix the reference velocity at 500 m as 30 cm s^{-1} to the south, the transport over the shelf below the thermocline is 2 Sv to the south with an average speed of 20 cm s^{-1}, consistent with the CUEA results at this latitude.

The general features of the mean circulation over the northern Peruvian shelf can be modeled by a two-layer wind-driven upwelling system (Fig. 5). The thermocline determines the upper layer thickness, recalling that the depths of the thermocline, oxycline and euphotic zone are approximately equal. The winds along the coast of northern Peru are generally favorable for upwelling with a mean wind velocity at Chimbote Airport for the last decade of 6.5 ms^{-1} from the south-southeast (ENFIELD, personal communication).

Fig. 5: Schematic model of the circulation.



The mean upper layer transport is equatorward and offshore, consistent with the wind drift and Ekman layer transport. In the lower layer, the mean transport is poleward and onshore, consistent with geostrophic transport and a two-dimensional cross-shelf mass balance.

The circulation, chemical and biological properties above the thermocline are substantially different from those below the thermocline. Noting this difference, we shall propose a mean budget for dissolved oxygen below the termocline. Within the lower layer, advection of dissolved oxygen is balanced by **in situ** production (P) and consumption (J),

$$\underset{(a)}{u\frac{\delta}{\delta x}[O_2]} + \underset{(b)}{v\frac{\delta}{\delta y}[O_2]} + \underset{(c)}{w\frac{\delta}{\delta z}[O_2]} + \underset{(d)}{P} = \underset{(e)}{J}, \quad (1)$$

where u, v, and w are the onshore, alongshore, and vertical velocities, respectively and $[O_2]$ is the concentration of dissolved oxygen.

Consider a parcel of water in the lower layer: with an average advection speed of 20 cm s^{-1}, it takes approximately 7.5 days for a parcel to travel from Pta. Chao to Pta. Culebras. During this transit, the left hand side of eqn. (1) represents a supply of oxygen to the parcel, where (a) is the onshore flux of oxygen due to upwelling, (b) is the alongshore flux, (c) is the vertical flux and (d) is the **in situ** production of oxygen. The consumption (e) of oxygen in the parcel should balance the supply if the proposed budget applies. The magnitude of each term in the balance will be estimated from the transect data for a 1 m wide strip in the lower layer from the coast to the shelf break averaged over the transit time of 7.5 days.

For a two-dimensional cross-shelf mass balance, the onshore transport below the thermocline equals the offshore Ekman transport above the thermocline. Using the mean wind at Chimbote Airport, the volume of upwelled water brought onto the shelf is 2 m^3 s^{-1} per m of coastline. If the average oxygen concentration of the upwelled water is 2 ml O_2 l^{-1} (a typical subeuphotic zone value), then upwelling supplied 3.1 x 10^4 g-atO_2 day^{-1} to the strip or 2.3 x 10^5 g-at O_2 during the 7.5 day transit time. (Table 2)

The volume of water with concentrations of oxygen less than 0.5 ml O_2 l^{-1} (oxygen-depleted water) increases from Pta. Chao to Pta. Culebras (north to south). If each transect is representative of the mean state of the parcel at that location and remembering that the alongshore geostrophic transport is approximately constant between the transects, then the alongshore flux of oxygen decreases to the south supplying oxygen to the strip. Following a parcel of water moving to the south, the **in situ** concentration supplies part of the consumed oxygen leading eventually to depletion of the **in situ** dissolved oxygen. The volume of oxygen-depleted water in the strip at Pta. Chao is 3 x 10^6 m^3 (35o/o of the total volume) and at Pta. Culebras is 9 x 10^6 m^3 (72o/o of the total volume). If the water at Pta. Chao began with an oxygen concentration characteristic of depths below the euphotic zone, but not oxygen-depleted (approximately 2 ml O_2 l^{-1}), then the **in situ** concentration supplies 7.8 x 10^5 g-at O_2 for the water to arrive at Pta. Culebras with an oxygen concentration of 0.5 ml O_2 l^{-1}. Thus, the net supply of oxygen to the strip due to the alongshore flux in the 7.5 day transit time is approximately 7.8 x 10^5 g-at O_2.

The vertical flux of oxygen occurs by exchange of water between the upper and lower layers due either to upwelling or vertical mixing. The vertical flux due to upwelling is presumably negligible, since the upwelling mass exchange is greatest near the coast where the oxygen concentrations in the lower layer are least. A crude estimate of the flux due to mixind can be obtained using an eddy diffusivity. For an eddy diffusivity of 1 cm^2 s^{-1} and a concentration difference of 5 ml O_2 l^{-1} across a 10 m oxycline, mixing supplies only 3 x 10^4 g-at O_2 over the 7.5 day transit time, much less than the horizontal fluxes.

No photosynthesis occurs in the lower layer to produce oxygen. When the **in situ** concentration of dissolved oxygen disappears, oxidation of organic matter can still occur through bacterial reduction of nitrate and nitrite. Denitrification is a virtual supply of oxygen to the water column. Over the whole shelf, the production of oxygen in the lower layer is negligible, but in local regions, denitrification can be very important in the oxygen budget.

The total supply of oxygen to the 1 m strip over the continental shelf in the 7.5 day transit time is approximately 1.1 x 10^6 g-at O_2 (Table 2).

Table 2: Oxygen budget for a 1 m strip of water during a 7.5 day transit below the thermocline from Pta. Chao to Pta. Culebras.

Oxygen Consumption	
oxidation of *in situ* standing stock	0.5 x 10^5 g-at O_2
oxidation of material from primary productivity	8.2 x 10^5
total consumption	0.9 x 10^6
Oxygen Supply	
from upwelling	2.3 x 10^5 g-at O_2
from *in situ* depletion	7.8 x 10^5
from vertical mixing	0.3 x 10^5
total supply	1.1 x 10^6

The alongshore flux of oxygen, estimated from the **in situ** depletion of oxygen in a parcel of water moving southward, is three times greater than the onshore flux due to upwelling.

Biology and the Oxygen Budget

If the proposed oxygen budget is valid, then the consumption of oxygen in the lower layer by oxidation of organic matter should balance the supply of oxygen. Over long time scales, all organic matter produced in the euphotic zone must be removed, either by oxidation, sedimentation or export to another location. If the organic matter resulting from primary productivity in the upper layer sinks to the lower layer as either senescent cells or fecal material and decomposes there, then the combustion of the upper layer productivity provides an upper bound for the oxygen consumption in the lower layer.

Assuming that most of the organic matter was sampled as chlorophyll a and phaeophytin a, then we can convert it to carbon using the ratios of LORENZEN (1968) and SHUMAN and LORENZEN (1975) and estimate the oxygen required to consume this organic matter according to the logic of REDFIELD (1958). If chlorophyll a and phaeophytin a sank below the oxycline rapidly enough that all of the organic matter was consumed over the shelf, then 4.6 x 10^4 g–at O_2 were required to oxidize all the organic matter in the water column off Pta. Chao. Consumption of the standing stock of organic matter required less oxygen than the estimated supply, but primary productivity of the northern shelf was high. During November, 1977, primary productivity on the inner shelf was high. At Sta. 71 on the Pta. Chao transect, the rate was 7.0 gC m^{-2} day^{-1} (HARRISON, personal communication) and at Sta. 321 on the Pta. Culebras transect, the rate was 12.6 gC m^{-2} day^{-1} (SELLNER, personal communication). Near the shelf break on the Pta. Chao transect, the rate was 1.7 gC m^{-2} day^{-1} (Sta. 75; HARRISON, personal communication), while on the Pta. Culebras transect, the rate near the shelf break was 11.1 gC m^{-2} day^{-1} (Sta. 314; SELLNER, personal communication). The average nearshore productivity was 10 gC m^{-2} day^{-1}, comparable to the data of RYTHER, et al. (1971). If we assume an average productivity over the inner half of the shelf of 10 gC m^{-2} day^{-1}, then oxidation of all the organic matter produced in the 7.5 day transit time required 8.2 x 10^5 g–at O_2. Thus, an approximate balance (to within 20 o/o) between the supply of oxygen from **in situ** depletion and from upwelling and the consumption by oxidation of organic matter existed (Table 2).

A number of possible routes for the combustion of organic material in the water column exist. The primary production and standing stock of phytoplankton are cycled through zooplankton, nekton, bacteria and the benthos. Each group of organisms converts plant material to its own tissues and uses oxygen in that conversion. How much plant material cycles through each "combustion furnace" is not known and is not important for this model. We assume that all plant material is combusted in the shelf area between Pta. Chao and Pta. Culebras. In addition to using oxygen during metabolism, the animal populations in the area convert phytoplankton (chlorophyll a) to fecal material (phaeophytin a) and thereby increase the sinking rate of organic material since the observed sinking rates for fecal pellets is 36–376 m day^{-1}, while that for living phytoplankton is 0–30 m day^{-1}, (PARSONS and TAKAHASHI, 1973). Accelerated sinking rates of organic material nearshore increases the likelihood of anoxia and hydrogen sulfide production near the bottom.

Because our oxygen budget is restricted to the shelf area, the maximum depth of the water column under consideration is 180 meters, less than the 200 m depth considered by MENZEL and RYTHER (1970) and MENZEL (1974) to be the depth above which most cycling of organic matter takes place. We are not attempting to describe global or large scale processes but to establish the possibility that over the wide continental shelf off northern Peru biological and chemical events in combination with the circulation may contribute regularly to the oxygen deficiency observed in Peruvian coastal waters (CODISPOTI et al., 1976; HAFFERTY, CODISPOTI and HUYER, 1978). The agreement of our calculations of oxygen consumption and supply to an order of magnitude suggests that other sources of consumption and supply are either small or in balance over the shelf.

Summary

A plausible picture of the circulation and oxygen budget over the wide continental shelf off northern Peru does emerge. Upwelling along the coast is driven by a favorable mean wind stress. Above the thermocline, the mean flow is equatorward and offshore, while below the thermocline, the mean flow is poleward and onshore. Within the euphotic zone, the primary productivity over the shelf is high. In a steady state regime, all of the organic matter produced in the euphotic zone must be removed from the water column by consumption, sedimentation or export. While the exact mechanisms of the removal of organic matter are not known, the oxidation of the organic matter created by primary productivity represents an upper bound on the consumption of oxygen within the southward flowing lower layer. Locally, the consumption of oxygen, must be balanced by supply from **in situ** depletion of dissolved oxygen, onshore transport of oxygen due to upwelling, and, indirectly, denitrification. Over the continental shelf of northern Peru between 9°S and 10°S, the **in situ** depletion is much greater than the rate of supply from upwelling and approximately balances the estimated rate of consumption of oxygen (Table 2).

Primary productivity is greatest inshore, giving a greater expected rate of consumption of oxygen nearshore than offshore. Since the estimated rate of consumption of oxygen is greater than the rate of supply due to upwelling, **in situ** depletion of oxygen must occur. As a result of the cross–shelf variation in the primary productivity, the concentration of oxygen decreases nearshore and complete depletion of dissolved oxygen first occurs adjacent to the shore. Since **in situ** depletion provides most of the oxygen to consume organic matter, the volume of oxygen–depleted water increases from north to south over the shelf. When the **in situ** concentration of oxygen has been exhausted, further oxidation of organic matter can occur through denitrification, the bacterial reduction of nitrate

to nitrite and, when the nitrate concentration is exhausted, of nitrite to gaseous nitrogen. Similar to the pattern for oxygen, denitrification first occurs adjacent to the shore and complete denitrification, resulting in sulfate reduction and hydrogen sulfide production, also occurs first near the shore and to the south of where oxygen depletion first occurs.

The above variations in the concentrations of oxygen, nitrate, and nitrite in the lower layer inferred from the oxygen budget are consistent with the actual variations observed over the continental shelf off northern Peru in November and December, 1977. North of Pta. Falsa, oxygen and nitrate concentrations are relatively high throughout the water column everywhere over the shelf and nitrite concentrations are low. At approximately 7°S, oxygen depletion occurs below 30 m in 50 m of water, but nitrate concentrations remain high. At 9°S, approximately half the lower layer is depleted in oxygen. Nitrate concentrations decreased inshore while nitrite concentrations increased with complete denitrification occurring very nearshore at the bottom. Further to the south at 10°S, almost all the lower layer is oxygen–depleted and a subsurface nitrite maximum occurs as nearshore denitrification increases. Consistent with these variations, sulphate–reducing bacteria, present only when denitrification has gone to completion, are not found in the surface sediments north of 7°S, but do occur in appreciable densities nearshore to the south (G. ROWE, personal communication).

CONCLUSIONS

A precarious balance exists between the oxygen consumption and supply in the southward flow below the thermocline over the continental shelf off northern Peru. The utilization of oxygen to consume organic matter produced by the large plant biomass in the euphotic zone exceeds the rate of supply of oxygen from upwelling. Depletion of **in situ** dissolved oxygen must occur to balance the consumption. When local depletion has gone to completion, denitrification can occur. Denitrification plays an important role in the oxygen balance and appears to be a common feature inshore over the southern portion of the shelf.

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REFERENCES

BRINK, K., J. ALLEN and R. SMITH. 1978. A study of low frequency fluctuations near the Peru coast. **J. Phys. Oceanogr.** 8: 1025–1041.

——— R. SMITH and D. HALPERN. 1978. A compendium of time series measurements from moored instrumentation during the MAM'77 phase of JOINT–II. CUEA Technical report 45, Oregon State University, Corvallis, Or. Ref. 79–17, 72 pp.

CODISPOTI, L., D. BISHOP, M. FRIEBERSTSHAUSER and G. FRIEDERICH. 1976. Data Report 35, Coastal Upwelling Ecosystem Analysis, 370 pp.

DOE, L. 1978. Project ICANE: A progress and data report on a Canada–Peru study of the Peruvian anchovy and its ecosystem, Bedford Institute of Oceanography, Halifax, Nova Scotia. Report Series BI–R–78–6.

DUGDALE, R., J. GOERING, R. BARBER, R. SMITH and T. PACKARD. 1977. Denitrification and hydrogen sulfide in the Peru upwelling region during 1976. **Deep–Sea Res.** 24: 601–608.

HAFFERTY, A., L. CODISPOTI and A. HUYER. 1978. Data Report 45, Coastal Upwelling Ecosystem Analysis, 779 pp.

LORENZEN, C. 1966. A method for the continuous measurement of **in vivo** chlorophyll concentration. **Deep–Sea Res.** 13: 223–227.

——— 1968. Carbon/chlorophyll relationships in an upwelling area. **Limnol. Oceanogr.** 13: 202–204.

MENZEL, D. 1974. Primary productivity, dissolved and particulate organic matter and the sites of oxidation of organic matter. **in** The Sea, v. 5; **edited** by R. Goldberg. John Wiley Interscience, New York, pp. 659–678.

——— and J. RYTHER. 1970. Distribution and cycling of organic matter in the ocean. **in** Organic Matter in Natural Waters, pp. 31–45; **edited** by D.W. Kood.

PARSONS, T. and M. TAKAHASHI. 1973. Biological Oceanographic Processes, Pergammon Press. 186 pp.

REDFIELD, A. 1958. The biological control of chemical factors in the environment. **Amer. Sci.** 46: 205–221.

ROJAS DE MENDIOLA, B. 1971. Some observations on the feeding of the Peruvian anchoveta **Engraulis ringens J.** in two regions of the Peruvian coast. **in** The Fertility of the Sea; **edited** by J.D. Costlow. Gordon and Breach. pp. 417–440.

RYTHER, J., D. MENZEL, E. HULBURT, C. LORENZEN and N. CORWIN. 1971. The production and utilization of organic matter in the Peru Coastal Current. **Inv. Pesq.** 35: 43–59.

SHUMAN, F. and C. LORENZEN. 1975. Quantitative degradation of chlorophyll by a marine herbivore. **Limnol Oceanogr.** 20: 580–586.

SLAWYK, G. and J. MACISAAC. 1972. The comparison of two automated ammonium methods in a region of coastal upwelling. **Deep–Sea Res.** 19: 521–524.

SMITH, R., D. ENFIELD, T. HOPKINS and R. PILLSBURY. 1971. The circulation in an upwelling ecosystem: The **Pisco** cruise. **Inv. Pesq.** 35: 1–24.

STRICKLAND, J. and T. PARSONS. 1968. A practical handbook of seawater analysis. **Fish. Res. Bd. Can. Bull.** 167: 311 pp.

WOOSTER, W., T. CHOW and I. BARRETT. 1965. Nitrite distribution in Peru Current waters. **J. Mar. Res.** 23: 210–221.

——— and M. GILMARTIN. 1961. The Peru–Chile Undercurrent. **J. Mar. Res.** 19: 97–122.

WYRTKI, K. 1963. The horizontal and vertical field of motion in the Peru Current. **Bull. Scripps Inst, Oceanogr.** 8: 313–346.

ZUTA, S.T. RIVERA and A. BUSTAMANTE. 1978. Hydrological aspects of the main upwelling areas off Peru. **in** Upwelling Ecosystems; **edited** by R. Boje and M. Tomczak. Springer–Verlag, Berlin.