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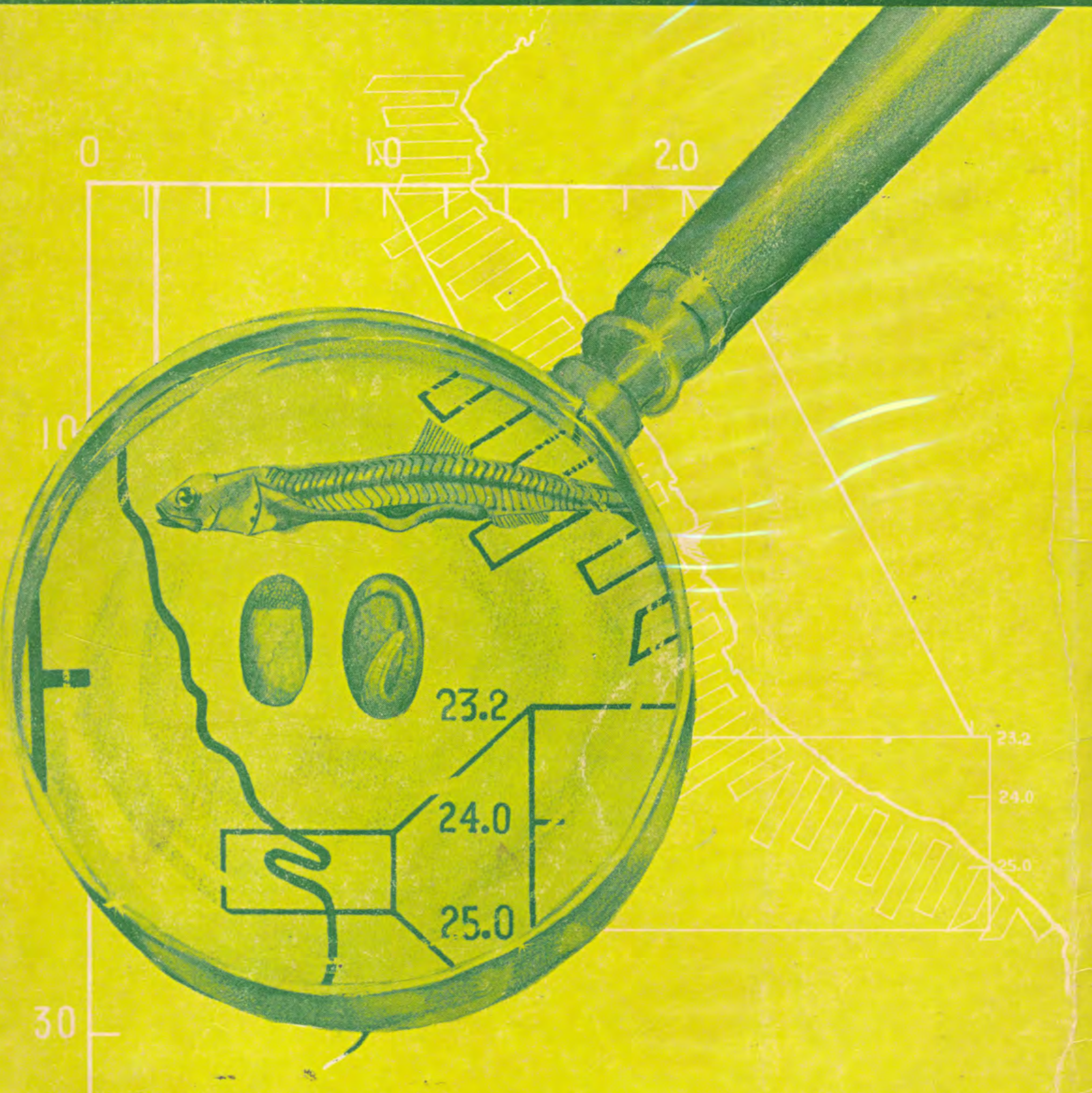

INVESTIGACION COOPERATIVA DE LA ANCHOVETA Y SU ECOSISTEMA-ICANE-ENTRE PERU Y CANADA

CALLAO 1981 PERU

ASPECTS OF VARIABILITY IN PERUVIAN COASTAL WATERS NEAR 9°S

by

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ABSTRACT

Physical observations from two cross-shelf transects near 8 and 10°S are consistent with those of other surveys but data from a more rapidly sampled 48-hour anchor station and a 36-hour drogue tracking station suggest that the physics in the area is more complex than previously thought. On the basis of temperature, salinity, dissolved oxygen concentrations, and static stability, we postulate that most of the upwelled water in this region is supplied by the eastward extensions of the Equatorial Undercurrent and the South Subsurface Equatorial Countercurrent. Simple spectral analysis of such features as the longshore component of the wind stress, sea level elevation, thermocline and mixed layer depths suggest that the distribution of variance in these parameters has time scales varying between 0.09 to > 24 cycles per day. Although our low confidence spectra do not adequately resolve the spectrum of the possible local and remote forcing mechanisms, they indicate the scales of the measurements needed to better resolve the variability in the physical environment as well as its coupling and interaction with biological and chemical environments.

RESUMEN

Las observaciones físicas en dos líneas a través de la plataforma cerca de los 8° y 10° S son consistentes con los datos de otros cruceros pero los obtenidos en una estación fija muestreada durante 48 horas junto con los de una estación de seguimiento de un ancla flotante (drogue) por 36 horas sugieren que la física del área es más compleja de lo que se creía. Considerando la temperatura, salinidad, concentraciones de oxígeno disuelto y la estabilidad estática, proponemos que la mayor parte del agua aflorada en esta región proviene de las extensiones orientales de la Corriente Submarina Ecuatorial y de la Contracorriente Sur Subsuperficial Ecuatorial. El análisis expectral simple de factores tales como el componente a lo largo de la costa de la fuerza del viento, la elevación del nivel del mar, la profundidad de la termoclina y de la capa de mezcla sugiere que la variancia de estos parámetros se da en escalas temporales que varían entre 0.09 y más de 24 ciclos por día. Aunque la baja confiabilidad de los expectros no resuelve adecuadamente la posible variedad de mecanismos actuantes cercanos y lejanos, sirven para indicar las escalas de las medidas que se necesitan para una mejor resolución de la variabilidad del ambiente físico así como su conexión e interacción con los ambientes químico y biológico.

INTRODUCTION

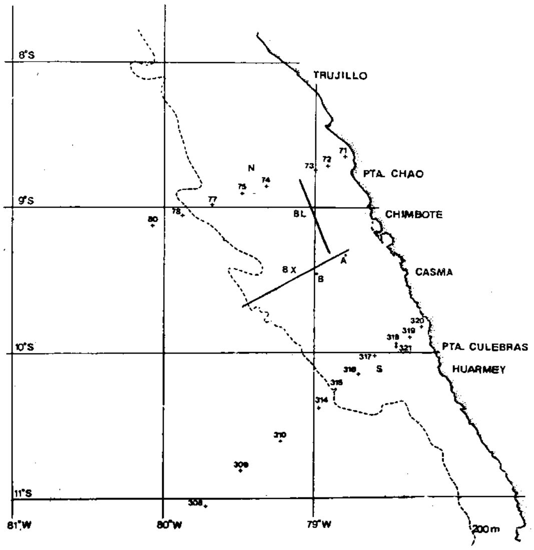
Peruvian coastal waters near the most persistent and intense upwelling area at 15°S have been the subject of intensive oceanographic surveys since 1961 but less attention has been afforded the biologically productive waters over the broad continental shelf between 6° and 12°S where upwelling is more sporadic and less intense. Previous surveys in this latter area have resulted in a reasonable understanding of the steady state physics there (c.f. Zuta, 1978) but the reasons for the dramatic variability of the physical and biological environments are not well understood. Much of the variability in the physical environment is thought to be caused by the passage of remotely (equatorially?) generated mechanisms such as poleward propagating trapped coastal waves (Smith, 1978; Kindle, 1979), fluctuations and changes in advective processes (Wooster and Gilmartin, 1961; Tsuchiya, 1975; Brink et al., 1978), variations in the local longshore component of the wind stress, and local topographic effects. However, the observational evidence necessary to determine the spectrum of the variability or its coupling and interaction with the biology and chemistry is still wanting. This is not surprising since the lengthy records of near continuous measurements from strategically located observation sites necessary to resolve the range of time (inter-annually to many cycles per day) and length (thousand of kilometers to a few centimeters) scales of the remote and local forcing mechanisms, would require large scale complex and costly surveys. Since these scales encompass those of many biological and chemical processes, it seems clear that until the spectrum of variability in the physical environment as well as its coupling and interaction with biological and chemical events is better understood, the validity of predictive ecosystem models which do not consider the environmental factors will be suspect.

Although observations from the small scale ICANE survey do not allow us to satisfactorily resolve the spectrum of variability in the physical environment they provide clues to the more important scales, hence to the relative importance of the likely forcing mechanisms. The focal point of this paper is an examination of the variability in the physical environment; a more detailed analysis of the environment is ongoing.

THE EXPERIMENT

Physical observations from stations (Fig. 1) along two cross-shelf transects, one (transect N) beginning near Punta Chao (8°39'S, 78°45'W) and extending 160 km offshore, and another (transect S) beginning some 220 km offshore and terminating near Punta Culebras (9°50'S, 78°10'W) (Richman and Smith, 1979), are consistent with those made during similar earlier surveys (Zuta, 1978) and are not elaborated on in this paper. However, at a 48-hour anchor station (Station A; 9°20'S, 78°50' W) some 40 CTD (conductivity-temperature-depth) casts were taken, including two nearly continuous time series of data obtained by yo-yo-ing the instrument through the water column, and at a 36-hour drogue tracking station (Station B, 9°39'S, 79°00'W), a total of 13 CTD casts was taken. The data from these stations are used to illustrate the small scale spatial and temporal variability in the physical environment. Where possible, high resolution temperature and salinity-versus-depth profiles (Herman, 1979) for a longshore mid-shelf transect (transect BL) and a cross-shelf transect (transect BX) are used to supplement the data set. Transect N was occupied from 5-7 November, Station B from 9-10 November, transect BL from 15-18 November, Station A from 19-20 November, transect BX from 22-23 November and transect S from 28-30 November, all in 1977.

Fig. 1 Observation sites: Punta Chao, north transect (N), Batfish longshore transect (BL), Batfish cross-shelf transect (BX), 48-hour anchor station (A), 36-hour drogue tracking station (B), Punta Culebras, south transect (S).



CHARACTERISTIC CIRCULATION AND WATER MASSES

Although advective processes are considered to be one of the main factors affecting the upwelling regimé over the broad continental shelf, the origins, strengths and variability of the current systems affecting the area are not well documented or understood. It is generally thought that the poleward flowing Peru-Chile Undercurrent (Wooster and Gilmartin, 1961) supplies most of the upwelling source waters between 5° and 12°S, but it is not clear whether the observed poleward flow over the shelf is an intrusion of the current over the shelf (Wyrtki, 1966) or a separate undercurrent altogether. The Peru-Chile Undercurrent is thought to originate near 5°S at the southern extension of the Equatorial Undercurrent (EUC) and the subsurface equatorial countercurrent (SSECC) but the relative amounts of water from each current system and hence the distributions of water properties advected along the coast are not known. Since these easterly flowing parental currents are known to shift their latitudinal axes and to vary in eastward penetration or velocity (White, 1971; Tsuchiya, 1975), it seems reasonable that the velocity and water composition of the resultant Undercurrent (s) which supply the upwelling source waters will also vary. Although complete reversals in the Undercurrent (s) have been reported (Wooster and Gilmartin, 1961; Schaffer, personal communication), recent moored current meter array measurements between 10 and 15°S suggest that this phenomenon could be caused by fluctuations in advective processes (Brink et al., 1978), interactions between the eastward flowing equatorial countercurrent and their flows (Tsuchiya, 1975) or simply by the passage of a poleward propagating disturbance (Smith, 1978).

The problem is that without better information on the advective processes, it is not possible to determine the relative importance of the various mechanisms which may be affecting other parts of the system. For example, although shear zones set up by the interaction of the eastward flowing equatorial countercurrents and their return flows might retain non-swimming organisms on the shelf long enough for them to benefit from the nutrient-rich upwelled water, the same effect could be achieved by the passage of a poleward propogating disturbance. Thus, although one is tempted to postulate that subtle changes in water mass characteristics due to advective process alter the chemistry, hence the biology of the area (Barber et al., 1971), the possibility that the biology alters the chemistry of the water (Dugale et al., 1977; Richman and Smith, 1979) is equally plausible. This suggests that one of the first steps in the understanding of this ecosystem should be the determination of the advective processes that affect it.

The paucity of information concerning the origins, velocities, and geographical positions of the current systems affecting the area and the aforementioned factors suggests caution in the use of water mass properties as indicators of the circulation patterns. Nevertheless, it is postulated here that a careful analysis of a full set of the water mass properties provides some important clues to the origins of the upwelled waters and their likely circulation patterns.

Distributions of temperature, salinity, nutrient and chemical properties of the waters affecting the northern and southern transects (Richman and Smith, 1979) show that cold (~15^{o}C), saline (~35.05^{o}/oo), nutrient-rich waters having low dissolved oxygen concentrations (< 1.5 ml 0^2 1^{-1}) flow onshore at or near the base of the shallow thermocline between the 25.8 and 26.1 isopycnals in response to a favourable longshore wind stress. A composite temperature-salinity (T-S) diagram of all the T-S data from the stations on transects N and S (Fig. 2) shows temperatures ranging from 7.5^{o}C at 500 meters to 22^{o}C at the surface and salinities ranging from 34.63^{o}/oo at 500 meters to 35.3^{o}/oo at the surface. Beyond the shelf break, mixing takes place along the straight line joining the deepest waters sampled and those near the base of th thermocline (16^{o}C, 35.1^{o}/oo) whilst over the shelf the predominant feature is a shallow subsurfac salinity maximum. When we superimpose the T-S diagram on a composite diagram of the characteristic temperatures and salinities of the water masses affecting the area (Fig. 3), the dilemma of water mass identification based on temperature and salinity characteristics alone becomes evident. That is, if our original supposition of the origin of the upwelled source waters is correct, it is clear that the use of temperature and salinity is not adequate to resolve how much water is EUC in origin and how much is SSECC in origin.

Fig. 2a Distribution of temperatures and salinities from transects N and S

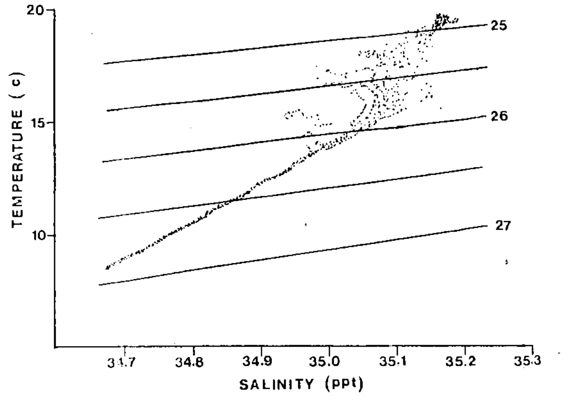


Fig. 2b Distribution of temperatures and salinities over the shelf area.

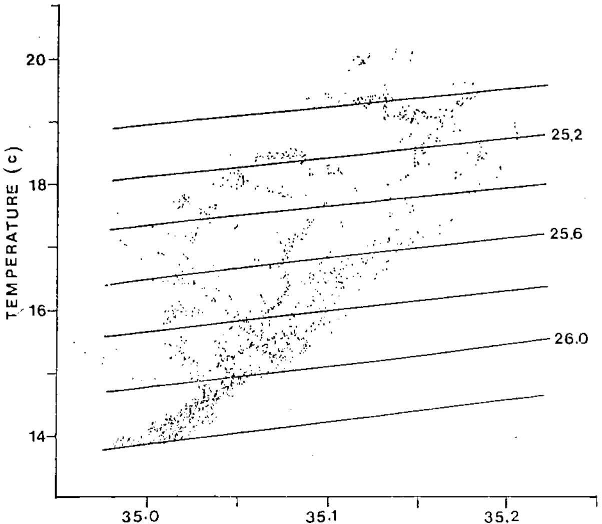
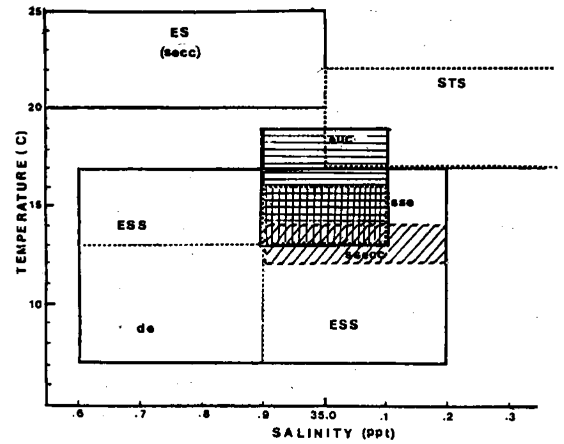


Fig. 3 Typical distributions of temperature and salinity for the primary water masses affecting the northern coastal area; Equatorial Subsurface water (ES), Subtropical Surface water (STS) and Equatorial Subsurface water (ESS). The possible subclassifications (shown in smaller print) are: south equatorial countercurrent water (SECC), equatorial undercurrent water (EUC), subsurface equatorial water (SSE), south subsurface equatorial countercurrent water (SSECC) and deep equatorial water (DE).



Eastpac surveys (Tsuchiya, 1975; White, 1971) show waters with alternate bands of high (> .35 ml O_2 l^{-1}) and low (< .35 ml O_2 l^{-1}) concentrations of dissolved oxygen on the 26.4 and 26.0 isopycnals and led to the suggestion that this might be attributable to the differences between the oxygen concentrations in the eastward flowing branches of the equatorial countercurrents and their return flows. In the ICANE survey dissolved oxygen concentrations on the 26.0 isopycnal on the southern transect agree with those observed during Eastpac studies (~.5ml O_2 l^{-1}) but those on the same isopycnal on the northern transect are higher by a factor of three. If one assumes that dissolved oxygen concentrations are conservative in nature, this evidence would suggest that there is more oxygen-rich EUC water to the north and more oxygen-poor SSECC water to the south. However, with only this evidence the possibility that the difference in the dissolved oxygen content of the waters between the two transects is due solely to biological activity cannot be ruled out. It is possible that other indicators such as trace metals might be used directly to assist in clarifying this problem of water-mass classification.

It appears, however, that the problem may be approached in a different way. Reid et al. (1977) postulate that a stability maximum should occur at the boundary between water masses of different origins and a minimum in the core of the water mass. We have computed the Brunt-Väisälä frequency ($N = [(-g\rho_0^{-1})(d\rho/dz)]^{1/2}$ at 5 meter intervals using density values 5 meters either side of the nominal value for the transect data (Figs. 4a, 4b) to test this hypothesis. The resulting three distinct minima may be postulated to represent the cores of the near surface STS water, the deeper EUC water and the near shelf-botton SSECC water. Relative proportions of the EUC and SSECC water at each transect as determined by this static stability method are consistent with those postulated by the dissolved oxygen concentration method and lend support to the hypothesis that advective processes between the EUC and SSECC may play an important role in determining water mass distributions in this area.

Fig. 4 Distribution of the Brunt-Väisälä frequency, suggesting 3 distinct water masses (3 minima).

4a. The Punta Chao transect (N)

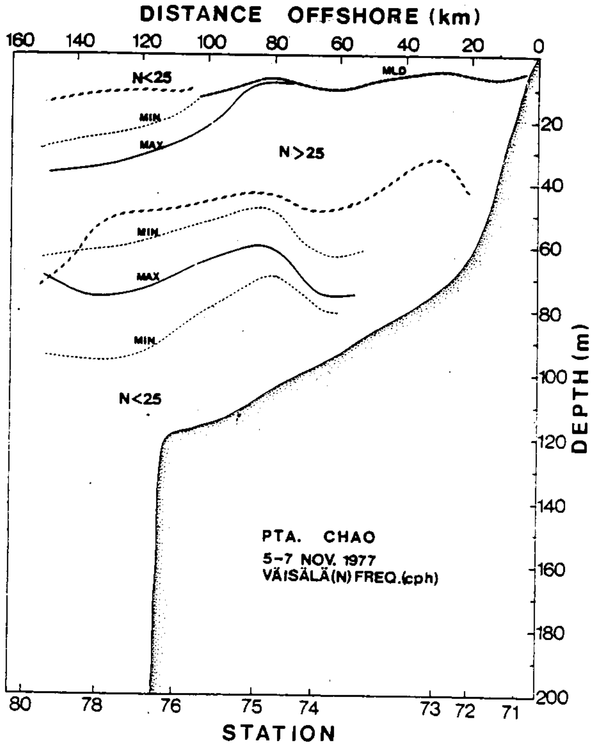
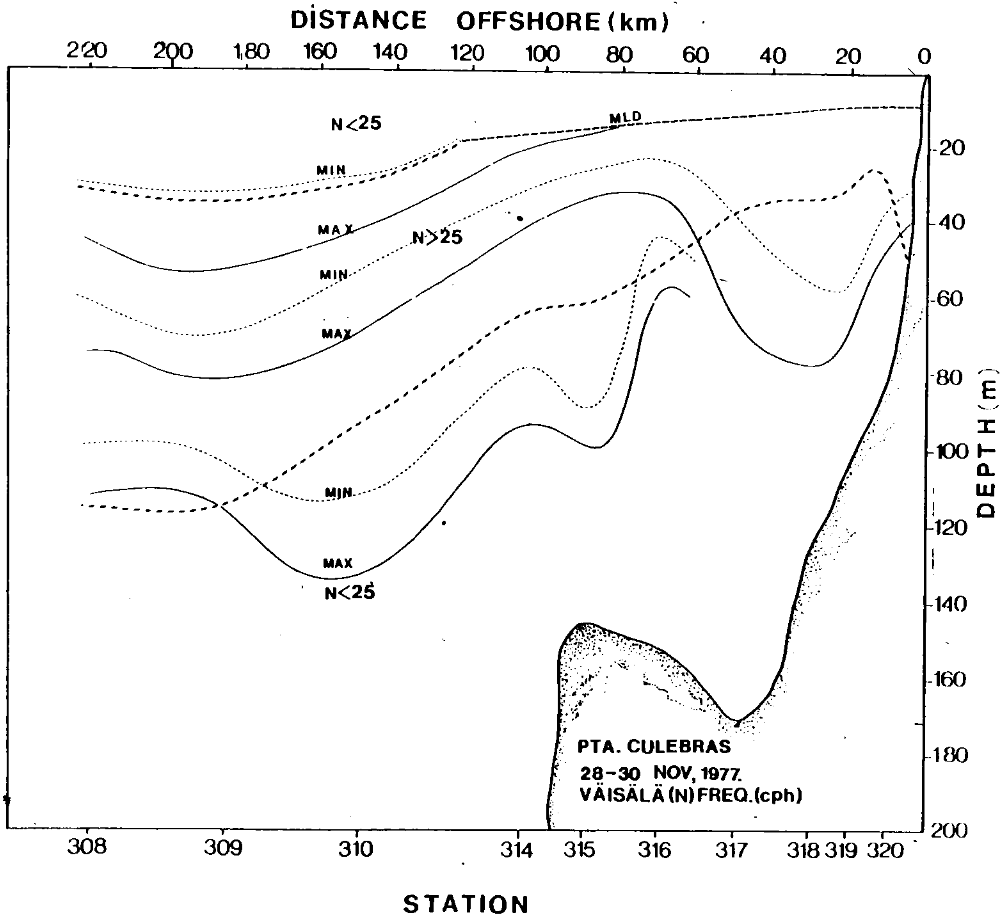


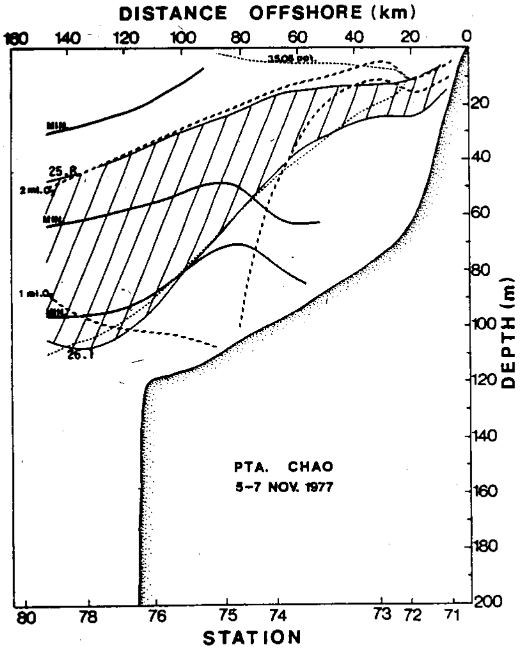
Fig. 4b The Punta Culebras transect (S)



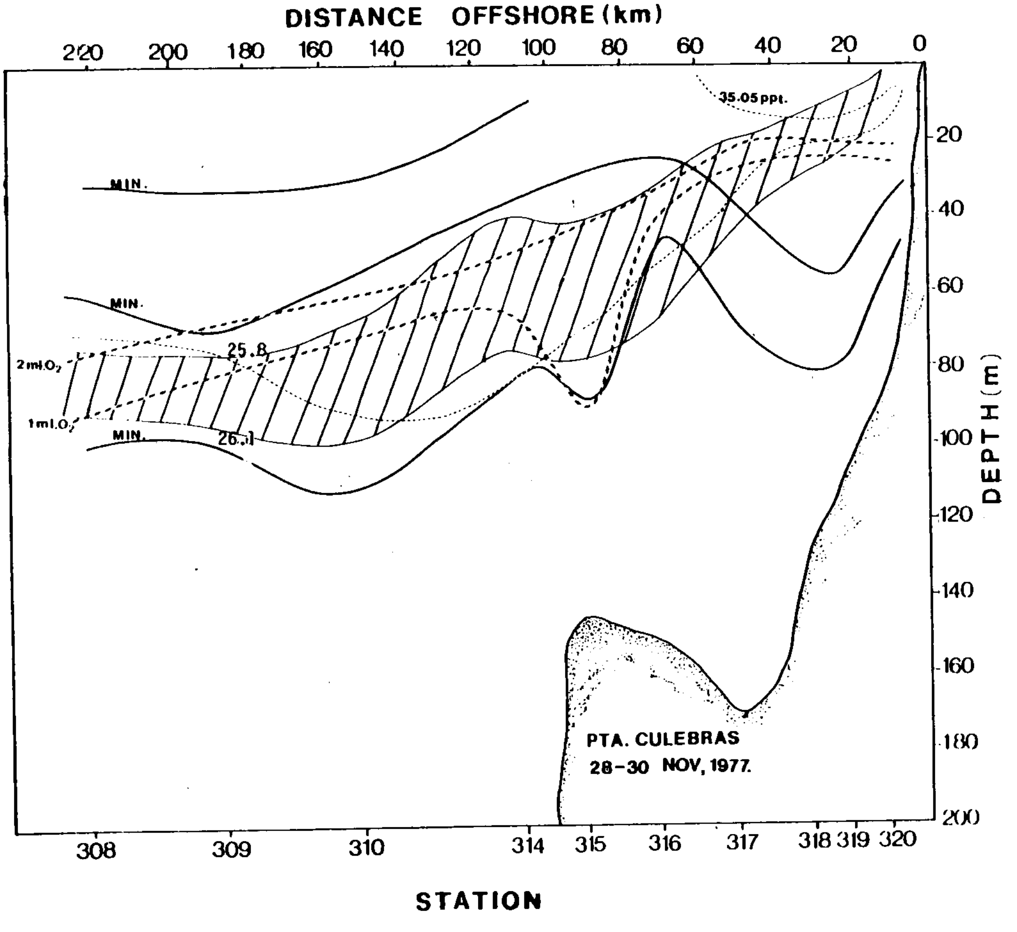
When the stability minima (water mass cores) and the dissolved oxygen isolines are superimposed on the 25.8 to 26.1 isopycnals (16 and 14°C isotherms), between which most of the upwelling takes place (Figs. 5a, 5b), a clearer picture of the source of upwelled waters emerges. On transect N, the two minima in the upwelling band suggest that the primary source of upwelled water is oxygen rich ($>$ 1.5 ml O_2 l^{-1}) EUC water with a lesser amount of deeper, colder (~14°C), oxygen poorer ($<$ 1 ml O_2 l^{-1}) SSECC water. On transect S, the upwelled water flows between the boundary of two water masses, the shallower exhibiting characteristics of EUC water and the deeper showing characteristics similar to that of SSECC water (S $>$ 34.9‰, O_2 $>$ 0.5 ml O_2 l^{-1}). Although the observed dissolved oxygen concentrations on transect S are slightly less than those observed in the core of the SSECC (Tsuchiya, 1975), the observations are not inconsistent with our interpretation since we may not have been sampling exactly in the core of the narrow (~ 150 km) SSECC. In fact, the core of the current could have been displaced along its latitudinal axis during the twenty three days between the transects or it may not have been exactly between the two transects in the first place. Therefore, while it is acknowledged that the biology may alter the oxygen content of the shelf waters, our obser-

Fig. 5 Composite of the Brunt-Väisälä frequency minima (water mass cores), 2 and 1 ml O_2 l^{-1} isolines, and the 35.05 ‰ isohalines located in or near the core of the upwelling source waters (between the 25.8 and 26.1 isopycnals).

5a. The Punta Chao transect (N)



5b The Punta Culebras transect (S)



vations extending out to the offshore waters (220 km offshore), suggest that the phenomenon is more likely to be due to variations in the advective processes.

On the basis of our observational evidence, it is clear that no single set of data is sufficient to establish the origin of the upwelled waters. However, when these observations are combined with evidence from previous surveys, a more sensible description of the origin of the upwelled water masses emerges. Water mass analysis based on T-S relationships, oxygen concentrations and static stability all suggest that the source waters are a combination of EUC water and SSECC water. Stability and dissolved oxygen concentrations suggest a greater proportion of EUC water at the northern transect whilst at the southern transect upwelled waters contain more SSECC water. The subsurface salinity maximum over the shelf is thus likely to be caused by the interaction of the onshore forcing of the thin layer of offshore Subtropical Surface water and the offshore wind driven current, although the possibility that it was formed remote from the survey area and is simply being advected through it cannot be ruled out.

WINDS

Any discussion of the forcing mechanisms affecting this upwelling regime requires a short discussion of the winds affecting the area. That is, interannual variations in the equatorial zonal winds may initiate the El Niño phenomenon and alter the positions and strengths of the major current systems affecting the area; seasonal variations in these same zonal winds may initiate the poleward propagating disturbances observed near 15°S (Smith, 1978) as well as shift the axis of the current systems, and variations in the local winds will affect both the local upwelling rate and the depth of the biologically important mixed layer. The wide range of scales of the postulated wind-driven forcing mechanisms suggests that important clues about these mechanisms might be discovered by correlating the wind spectra at various locations with that of other pertinent information such as sea-levels, currents, and the distribution of various water mass properties. Although our data set is not suitable for this analysis, it is possible to carry out a simple analysis of the distribution of variance in the area winds to obtain information concerning the scales of the wind-driven forcing mechanisms.

The spectrum of a three-month record of the mean daily winds at Chimbote (Fig. 6) determined by Fourier analysis (N = 90, half Tukey filter length = 8, Δt = 1 day), although poorly resolved, generally agrees with the spectrum of the longshore component of the winds near 15°S (Smith, 1978). A barely significant (80°/o confidence interval; Jenkins and Watts, 1968, p 82), rather broad response centered near 0.065 cpd, compares favourably with that determined by Smith (1978) and the suggested responses near 0.18 cpd and 0.28 cpd are also near those observed at 15°S. Our higher frequency response (> .35 cpd) is an order of magnitude more energetic than that at 15°S and suggests that higher frequency wind-driven mechanisms are more important in the Chimbote region than one would anticipate based on the difference in topographic features affecting the wind regimes between the two areas. The spectrum of the alongshore component of the wind stress from the Baffin observations during November (Fig. 7) determined by the same techniques (N = 32, Δt = 6 hours, 8 degrees of freedom) support this posutlation in that the magnitude of the response at 1.5 cpd is nearly the same as that at 0.065 cpd. Since only the low frequency (< .5 cpd) effects were analyzed at 15°S, a direct comparison between the higher frequency responses between the wind regimes in the two areas cannot be made.

Fig. 6 Distribution of variance in the daily mean winds at Chimbote (N=92, ν=16, Δt = 1 day)

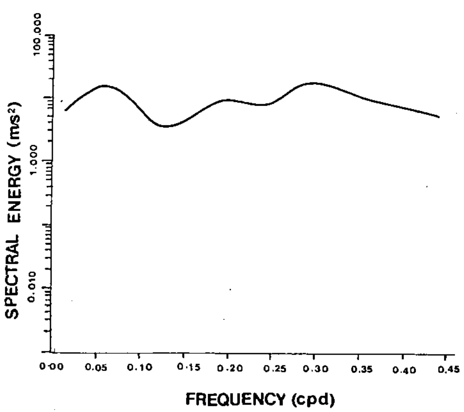
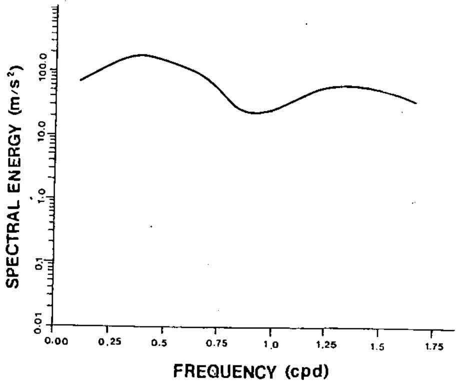


Fig. 7 Distribution of variance in the longshore component of the windstress from the Baffin's observations (N=32, ν=8, Δt = 6 hours)



It is not clear what effects the higher frequency wind responses have on the local upwelling. More specifically, although the characteristic spin-up time of an upwelling system is one inertial period, higher frequency variations (semi-diurnally) could have an effect on the local upwelling rate. The bi-monthly periodicity in the winds is similar to the characteristic periods of coastal trapped waves and although it is not likely they could initiate an El Niño (Wyrtki, 1967) they could easily effect displacements in the current systems affecting the area.

The close to unity ratio between the measured onshore transport and that predicted by simple Ekman dynamics ($M = \tau_y (\rho f)^{-1}$) found by Brink et al. (1978) near 15°S suggests that the onshore transport for the survey area was 2.5 $m^2 s^{-1}$ ($\bar{\tau}_y = \rho_{air} C_D U_{10}^2 \cong 0.67$ dynes cm^{-2} - $\bar{\tau}_y$ was computed from the 6-h Baffin wind observations). In general, most of the wind measurements were taken outside the internal Rossby radius of deformation, or the primary scale for upwelling (~ 22 km for the survey area), but as we could not establish any weakening or strengthening trend of the winds across the shelf, we feel justified in using these observations to calculate the onshore transport. Although no current meter data were available to demonstrate whether Ekman dynamics are valid this close to the equator where the Coriolis parameter becomes vanishingly small, our calculated transport is comparable to that measured at Callao (Zuta, 1978).

Variability in the Physical Environment.

When interpreting the data from a survey, or using these data to verify a model, one of the first questions that must be asked is "Are the data representative of the actual conditions?" Since the instrumentation required to collect high quality, high resolution oceanographic data has only been in use for a decade or so, it is not surprising that the data base necessary to better understand the dynamics of this environment is wanting. In this section we use our small amount of high resolution data to illustrate potential misinterpretations of more generalized observations.

The contoured time series of the distributions of temperature and salinity with depth from the 40 CTD casts taken at the 48-hour anchor station (Sta A, Figs. 8a, 8b) and those determined from the 13 CTD casts at the 36-hour drogue tracking station (Sta B, Fig. 8c) illustrate the dramatic variability in the sea surface temperature and the depth of the isotherms (isopycnals) and isohalines. At Sta A, the sea surface temperature varied by as much as 0.5°C over a 30-minute interval and the depth of the 16°C isotherm (25.8 isopycnal) varied by over 5 meters between observations taken 5 minutes apart and up to 15 meters between observations taken two hours apart. Similar variability was observed at Sta B with the depth of the thermocline varying by as much as 13 meters over a three hour period. At this station, both the depth of the thermocline ($Z = 71.3m$, $\sigma = 7.0m$) and the depth of the 14°C isotherm ($Z = 71.3m$, $\sigma = 5.8m$) show considerably more variability than those at Sta A where the mean thermocline depth was 21.2m ($\sigma = 3.8m$) and the mean depth of the 14°C isotherm was 72.3m ($\sigma = 2.3m$). Although the standard deviation in the thermocline depth

Fig. 8a Distribution of the isotherms and isohalines with depth at anchor station A.

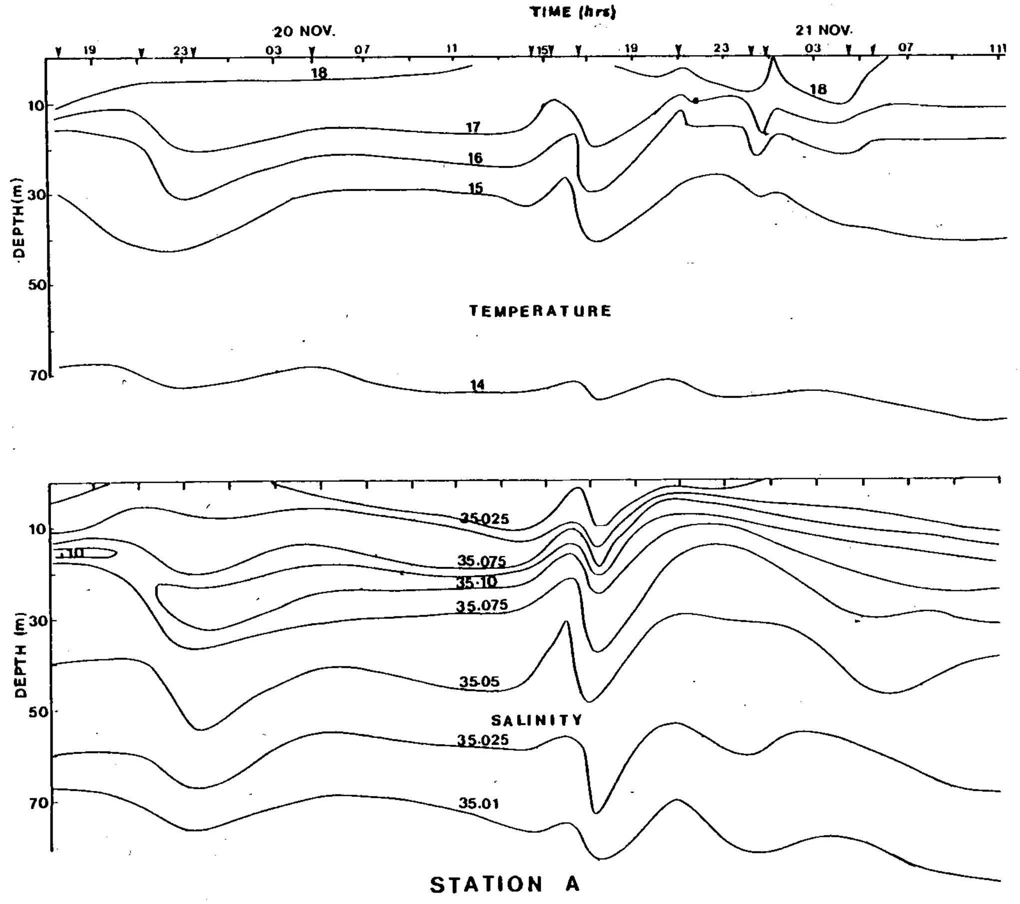


Fig. 8b Distribution of isotherms and isohalines with depth obtained from the yo-yo CTD casts (Δt = 5 min, Δt = 2.5 min)

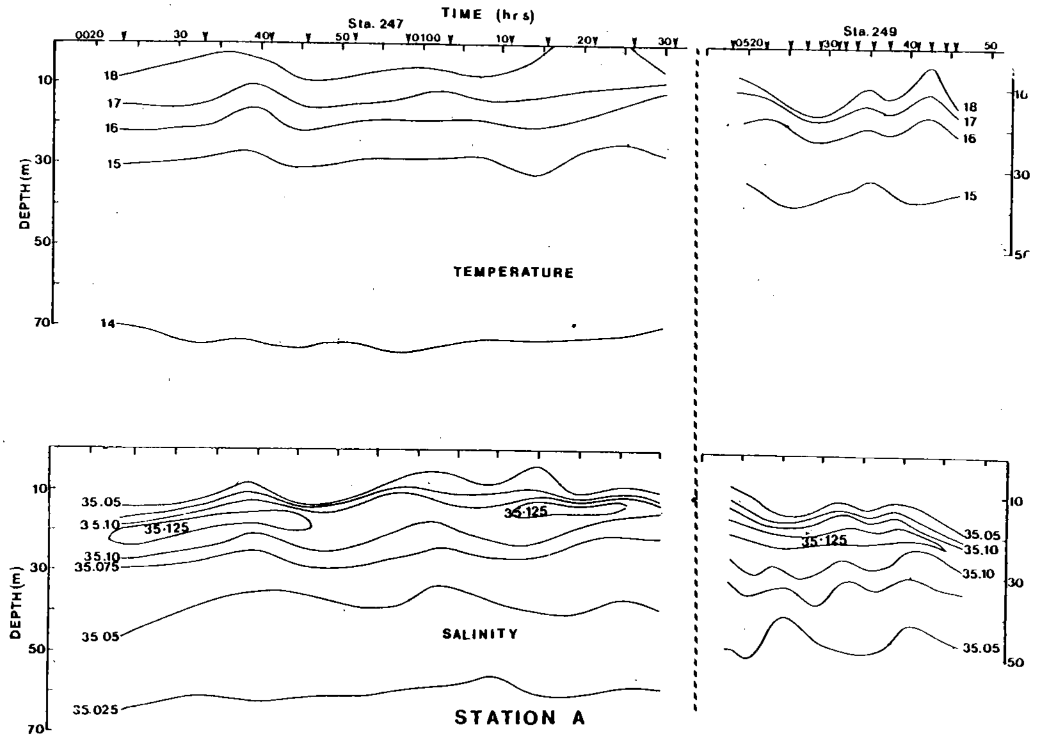
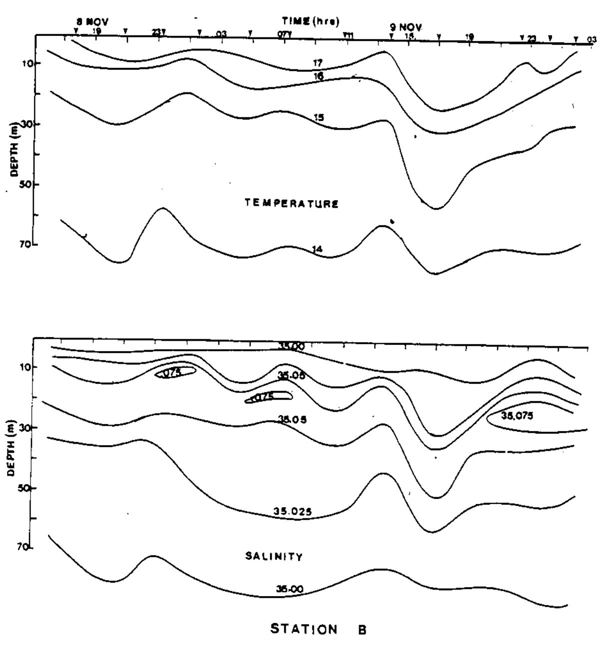


Fig. 8c Distribution of isotherms and isohalines with depth during tracking station B.



decreases with more frequent sampling ($\sigma = 2.9$m for 2.5 and 5 minute sampling intervals at Sta A), the sampling intervals used to compute the above statistics were similar. It is not known whether the difference in the standard deviations in thermocline depths between the two stations was due to local topographical features, the time delay between the stations (12 days), or simply small scale spatial effects (the radius of Sta B was approximately 6 km). The question at hand is whether or not these standard deviations can be extrapolated to those at the midshelf transect stations; and if so, what does one use for standard deviations (2.9, 3.8 or 7.0 meters) when determining the thermocline depth? Further, if similar variations in the isotherm (isopycnal) depths are observed closer to shore (Schaffer's data suggests they are), the fallacy of using single CTD observations to determine the vertical upwelling velocities by the displacement of isopycnals is evident. That is, using random values of the 26.0 σ_T isopycnal separated by 24 hours, we would calculate upwelling velocities ranging from 8.5×10^{-4} cms^{-1} to -7.3×10^{-4} cms^{-1} (downwelling). This temporal and spatial variability in the depth of the isotherms (isopycnals) also suggests that the use of observations from single CTD casts along a transect to calculate the geostrophic shear between stations might not be valid (Herman, this publication).

The contoured isohalines appear to be closely correlated with the movement of the isotherms and in addition to indicating a main subsurface salinity maximum, show small pockets of higher salinity water within this main salinity maximun. It is not clear whether these reflect an advective process or are simply results of pinching-off from a thin layer of more saline water. In any event, they clearly illustrate the requirement for higher resolution sampling techniques.

The contoured time series of the depth of the isotherms and isohalines are not adequate to allow us to resolve the spectrum of all the possible remote and local forcing mechanisms, but a simple Fourier analysis of the contoured data does allow us to make crude estimates of the relative effects of the predominant mechanisms. Due to the short length of the records, no filtering could be used, hence there is the risk that the spectra may be aliased and as such, are used as indicators of trends only. The combined spectrum of the thermocline depth shows the distribution of variance to be roughly partitioned between a low frequency band centered near 1.5 - 2 cpd (0.6 - 0.8 cph) (the low frequency cutoff) and a slightly less energetic high frequency band centered around 27 cycles per day. (Fig. 9). The lower frequency (1-2 cpd) response has a similar time scale to that of the Baffin wind spectrum, and suggests that bi-daily wind cycles (or tidal effects) are important in modulating the thermocline. The effects of high frequency internal wave activity between .6 and 6 cph also appear to be important in modifying the thermocline depth. Due to the short sampling period, we cannot estimate the effects of the lower frequency (< 1 cpd) mechanisms on the thermocline depth, but if they are correlated with the wind, one would expect to observe the thermocline depth to also vary with periods of 3.5, 5.5, and 15 days.

The mean depth of the biologically important mixed layer at stations A and B is only 9 meters whilst near 15^{o}S, it was 28 to 50 meters in depth (Brink **et al.**, 1978). Our time series of the mixed layer depth at stations A and B (Fig. 10) shows the depth varying by as much as 4 meters between observations taken 5 minutes apart, up to 8 meters between observations taken two hours apart, and up to 11 meters between observations taken six hours apart. The unfiltered spectra of the mixed layer depths (Fig. 11), although poorly resolved, suggest the variance is nearly equally partitioned between the low (~ .05 cph) and high (> 1 cph) frequency bands. This similarity between the mixed layer depth and isotherm depth distributions of variance suggests that similar forcing mechanisms affect both parameters, but does not explain why the mixed layer depths are so much deeper near 15^{o}S. If, as suggested by the spectra of variance, the primary mechanisms determining the mixed layer depths (heating, Niiler, 1975; and windstress) are similar for both areas (in spite of the seasonal differences between observations), one would expect the mixed layer depths at 15^{o}S and 9^{o}S to be more closely correlated. The disparity suggests that other (invariant?) factors such as stratification, topography, or advective processes might also be playing important roles in determining mixed layer depths and illustrates the danger of extrapolating observations between survey sites that may be affected by different mechanisms.

Hourly observations of sea level elevations at Chimbote (generously provided by S. Zuta) allow us to estimate the distribution of variance in the sea level elevations. The unfiltered spectrum of the

Fig. 9 Distribution of variance in the contoured depth of the 16°C isotherm at Stas. A and B.

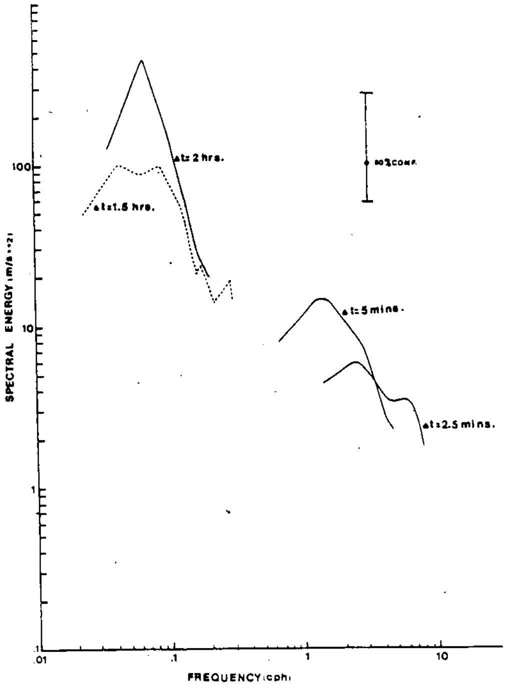
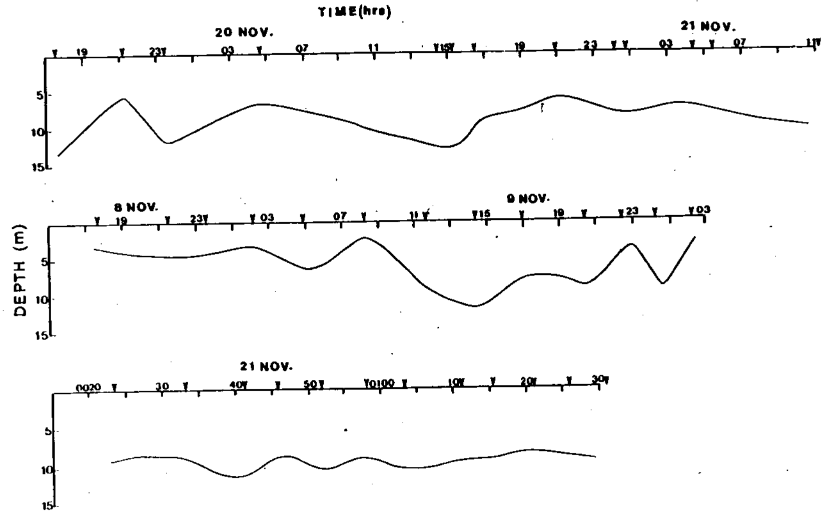
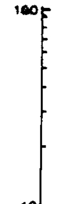


Fig. 10 Distributions of the depth of the biologically important mixed layer at Sta A (Nov. 20-21) and Sta B (Nov 8-9)

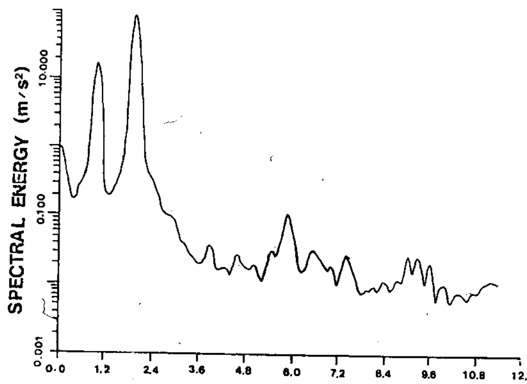


Fiq. 11 Distribution of variance in the contoured mixed layer depths at Stas A and E



sea level elevations (Fig. 12) indicates that most of the sea level changes were due to the M_2 and K_2 tides. When these tides are filtered out, we observe a significant low frequency (~ 0.09 cpd) response (Fig. 13) suggestive of either lunar fortnightly tides or a coastal trapped wave activity.

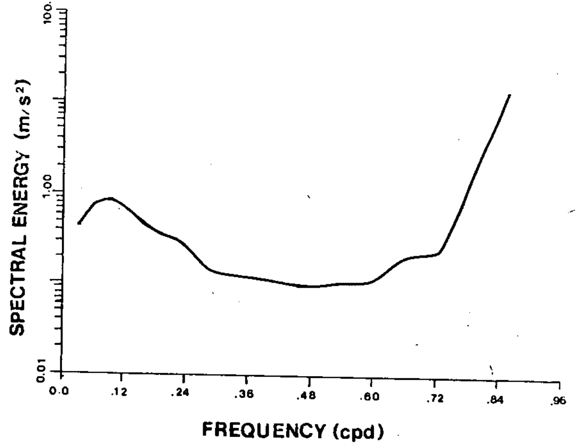
Fig. 12 Unfiltered spectrum of the sea level elevation at Chimbote (N=1440, ν= 16,Δt = 1 hr)



Concluding Remarks

Although our records are clearly not adequate for resolving all the forcing functions, they suggest that the major part of the variance in our observations has characteristic time scales of .09, 1, 2 and > 20 cpd, indicating that more complex sampling strategies are required on future surveys. Not only is it necessary to measure the longer term (at least seasonal) variability in the winds, currents, sea level elevations, water column temperatures and salinities, but samples must be taken rapidly enough to resolve the internal wave field. Moreover, since many of the remote forcing mechanisms are thought to originate near the equatorial region, the sampling grid must be large enough to allow these mechanisms to be resolved, while maintaining a finer grid to resolve the small scale mechanisms on selected sites within it.

Fig. 13 Low frequency distribution of variance in the sea-level elevation at Chimbote (decimation = 12 hours, ν=16)



Our simple analysis suggests that the ecosystem in the area of 9°S should not be considered 'closed' for the purpose of ecosystem predictive models. In this area, where so many mechanisms seem to be important, any simple model based on a limited number of parameters should give balances of the right order of magnitude. However, observational evidence necessary to validate or test a more complex practically predictive ecosystem model is still wanting. Our evidence for high variability in the physical environment suggests that the first priority of future studies must be to resolve the spectrum of variability resulting from both local and remote mechanisms (advective processes, wind driven mechanisms, poleward propagating trapped coastal waves, tidal effects, and internal wave processes). After the forcing mechanisms have been clearly categorized, simple correlation techniques should enable us to determine (and perhaps predict) their effects on the physical, chemical and biological environments in any particular area. Given this basic understanding of the system, it may turn out that the measurement of a few simple parameters will permit prediction of fish stock production and availability. In the absence of such understanding the observed physical complexity suggests that the likelihood of finding a long-standing simple correlation between fixed sets of biological and physical parameters is low.

REFERENCES

BARBER, R., R. DUGALE, J. MACISAAC and R. SMITH. 1971. Variations in the phytoplankton growth associated with the source and conditioning of upwelled water. **Inv. Pesq.** 35 (1) : 171-193.

BRINK, K., J. ALLEN and R. SMITH. 1978. A sutdy of low-frequency fluctuations near the Peru coast. **Journal of Physical Oceanography.** 8 : 1025-1041.

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

KINDLE, J. 1979. Equatorial Pacific Ocean Variability – seasonal and El Niño Time Scales. Ph. D. Thesis, Florida State University. 134 pp.

NIILER, P. 1975. Deepening of the wind-mixed layer. **Journal of Marine Research.** 4 : 405-423.

REID, J., W. NOWLIN and W. PATZERT. 1977. On the characteristics and circulation of the south-western Atlantic Ocean. **J. Phys. Oceanogr.** 7 : 62-91.

RICHMAN, J. and S. SMITH. 1979. On the possible enhacement of oxygen depletion in the coastal waters of Peru between 6° S and 11°S. (This volume).

SMITH, R. 1978. Poleward propagating pertubations in currents and sea levels along the Peru coast. **Journal of Geophysical Research.** 83 : 6083-6092.

TSUCHIYA, M. 1975. Subsurface countercurrents in the eastern equatorial Pacific Ocean. **Journal of Marine Research.** 33 (Supplement) : 145-175.

WHITE, W. 1971. The westward extension of the low-oxyty distribution in the Pacific Ocean off the west coast of South America. **Journal of Geophysical Research.** 76 : 5842-5851.

WOOSTER, W. and M. GILMARTIN. 1971. The Peru-Chile Undercurrent. **Journal of Marine Research.** 19: 97-122.

WYRTKI, K. 1966. Oceanography of the Eastern Equatorial Pacific Ocean. **Oceanographic Marine Biological Annual Review.** 4 : 34-68.

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.