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Hydrographic variability in an upwelling area off northern Baja California in June 1976

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ABSTRACT

Hydrographic, wind and current observations were made near Punta Colonet, Baja California at the peak of the upwelling season in June 1976. The mean hydrographic fields were typical of the seasonal mean upwelling over the continental shelf and the poleward undercurrent confined to a narrow zone (<20 km) over the slope. The density field exhibited a response to variation of the alongshore component of wind velocity. Stronger winds were followed by upwarping of the shallow isosurfaces over the inner shelf and complete vertical mixing within about 7 km of shore. The effect of the prominent cape of Punta Colonet, evident at the surface as a tongue-like structure of colder water oriented down-stream and offshore of the point, was not discernible at 20 m depth. One day of current profiles indicated strong equatorward flow in the upper layer decreasing uniformly with depth. The cross-shelf flow was variable and weak in the mean. The hydrographic data over the continental slope suggested the width of the undercurrent and presumably its strength varied greatly over periods of days.

1. Introduction

The nearshore waters off Baja California have been studied relatively little, in contrast to the areas beyond the continental shelf which have been subject to extensive scrutiny over the last thirty years by the California Co-operative Oceanic Fisheries Investigations Program (CalCOFI, Atlas Series, 1963; Reid et al., 1958; Hickey, 1979). Recent work in areas of eastern boundary currents has indicated a high degree of variability on time scales of the order of days of physical parameters over the slope and shelf, e.g. Huyer *et al.*, (1974); Barton *et al.*, (1977). This variability is intrinsically related to the phenomenon of coastal upwelling, which is generally considered a mesoscale response of the upper few hundred meters to changes in the alongshore component of the surface wind stress (Smith, 1968). A major effect of upwelling is the introduction into the surface layers of colder,

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higher nutrient content water from deeper levels. Regions of upwelling are for this reason the sites of productive fisheries and economically important.

Off northern Baja California the twenty year monthly mean winds have an equatorward component year round (Bakun, *1975),* which implies year round coastal upwelling although obviously at specific times the wind might be unfavorable for upwelling. The maximum equatorward component occurs in the mean in May and June. In June *1976,* a program of hydrographic, wind and current measurements was carried out in a *30* x *30* km^2 region near Punta Colonet, 31N. The area of study (Fig. 1) was chosen on the basis of its position in the center of a region of uniform bottom topography. It was placed off and to the south of the prominent coastal feature, Punta Colonet, since it is believed that such capes may often be associated with areas of enhanced upwelling or upwelling plumes. Also, it was off Punta Colonet that Wooster and Jones *(1970)* demonstrated the existence of a hydrographically well-defined undercurrent flowing north along the continental slope. The objective of the program was to examine the variability of the hydrographic fields over the continental shelf and slope principally in relation to the wind but also with respect to the limited current observations which would be available.

2. Data

Two occupations of the grid of hydrographic stations shown in Figure 1 and eleven occupations of the hydrographic line C off Punta San Telmo were made with a conductivity/temperature/depth (CTD) probe, Nansen bottles and bathythermographs. At an anchor station 34 hours of half-hourly hydrographic casts were obtained. During the period of the study, 8-26 June, wind observations were made at 10 m height above ground level at Punta San Jacinto with a Weather Measure anemometer to obtain 10-minute averages of wind speed and direction each hour. At three coastal sites, Punta San Telmo, Los Chichos and Punta San Jacinto, bucket temperatures were obtained daily at approximately the same time each morning. At a mid-shelf position on line C, a series of profiles of current was obtained over one day. A profiling current meter (PCM) similar to that described by Düing and Johnson *(1972)* and consisting of a modified Aanderaa current meter in a buoyant housing was used. A summary of the complete data set from the study and its processing is given by Morales *et al., (1978).* All times in this report are Pacific Standard Time (Time Zone 4).

3. Results

a. Winds and coastal surface temperatures. The time series of wind speed and direction observations from Punta San Jacinto were resolved into components

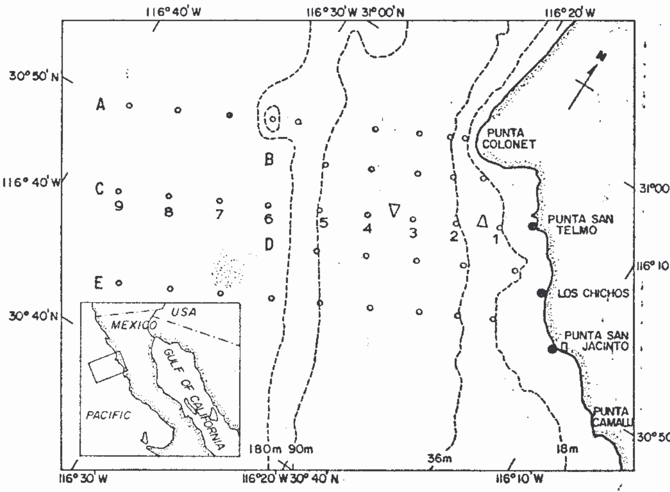

Figure 1. Location and chart of study area; ○—hydrographic stations, △—hydrographic anchor station, ▽—current profiles anchor station, □—anemometer site, ●—coastal temperature sites.

parallel and perpendicular to the dominant trend of the bottom topography *(330°T),* as shown in Figure 2. While both components showed strong diurnal variation related to the seabreeze-landbreeze cycle, the alongshore component showed more variation at lower frequencies than the cross-shore component. This is clearly seen in the data filtered with a 24-hour running mean, indicated by the heavy line in the figure. Detailed analysis of the wind data has been made by Amador (1978), but here it suffices to note some general characteristics of the daily-averaged along-shore component. It was equatorward for all but the last two days of the series, i.e. predominantly upwelling-favorable. It decreased slowly in magnitude from 8 to 17 June with the exception of 11 and 15 June when stronger pulses of equatorward wind occurred. From 17 June to late 21 June, it increased rapidly in magnitude and then, even more rapidly, decreased to zero and weak northward values on the final days of the study.

Comparison of the coastal wind and coastal seasurface temperature series, also shown in Figure 2, indicated that the changing wind conditions were associated with varying intensities of upwelling. A marked initial drop in temperature was followed by a gradual warming phase contemporaneous with the weakening trend in equatorward wind speed. The equatorward pulses of 11 and 15 June had, if any, little noticeable effect on the warming trend but the major increase in magnitude of the equatorward component of wind velocity of 17 to 22 June apparently produced the second marked fall in temperature beginning 20 June. At the very end of the series, the several days of low wind velocity were accompanied by the appearance of a new tendency towards higher temperature.

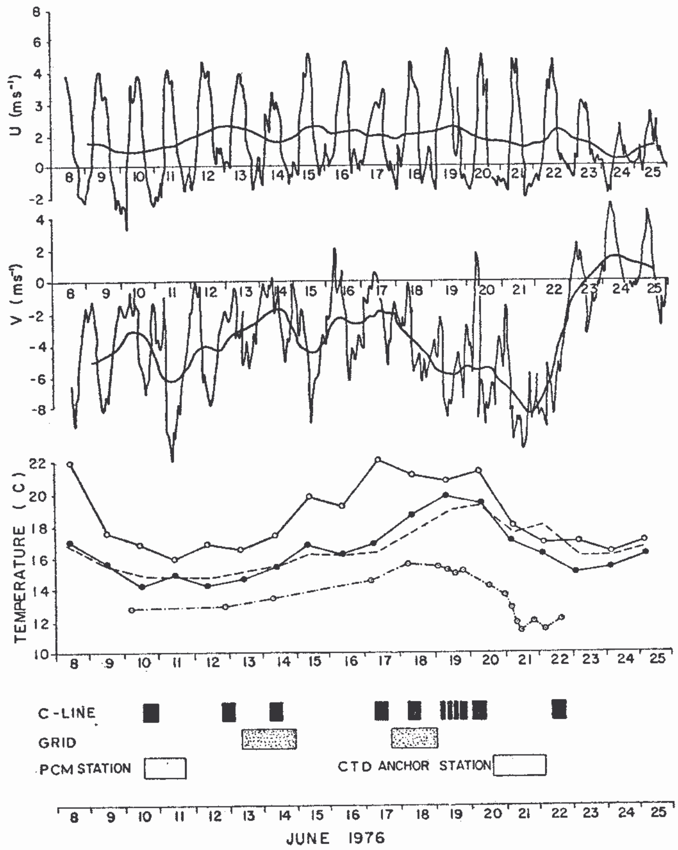

Figure 2. From top to bottom: Time series of onshore-offshore (u) and alongshore components (v) of wind observed at Punta San Jacinto with onshore and poleward values positive (low-passed wind, filtered by a 24-hour running mean, is indicated by the heavier line); time series of daily observed surface temperatures at coastal sites (●———●) Punta San Telmo, (○———○) Los Chichos, (– – – –) Punta San Jacinto, and at hydrographic station C1 (⊙– • –⊙); at bottom, calendar of hydrographic occupations of line C, the larger grid, and the two anchor stations.

It would appear then that variations in intensity of the equatorward wind component were followed by variations in the intensity of upwelling. Although the temperature values were different at the three coastal sites, the observed changes were similar. The range of variation was slightly less than 6 C. Because the temperatures were sampled only once per day the series is aliased, but probably not seriously as daily temperature variations are less than 2 C in this area. The lagged correlation between temperature at San Telmo directly opposite the frequently sampled line C, and daily mean alongshore wind stress gave a maximum correla-

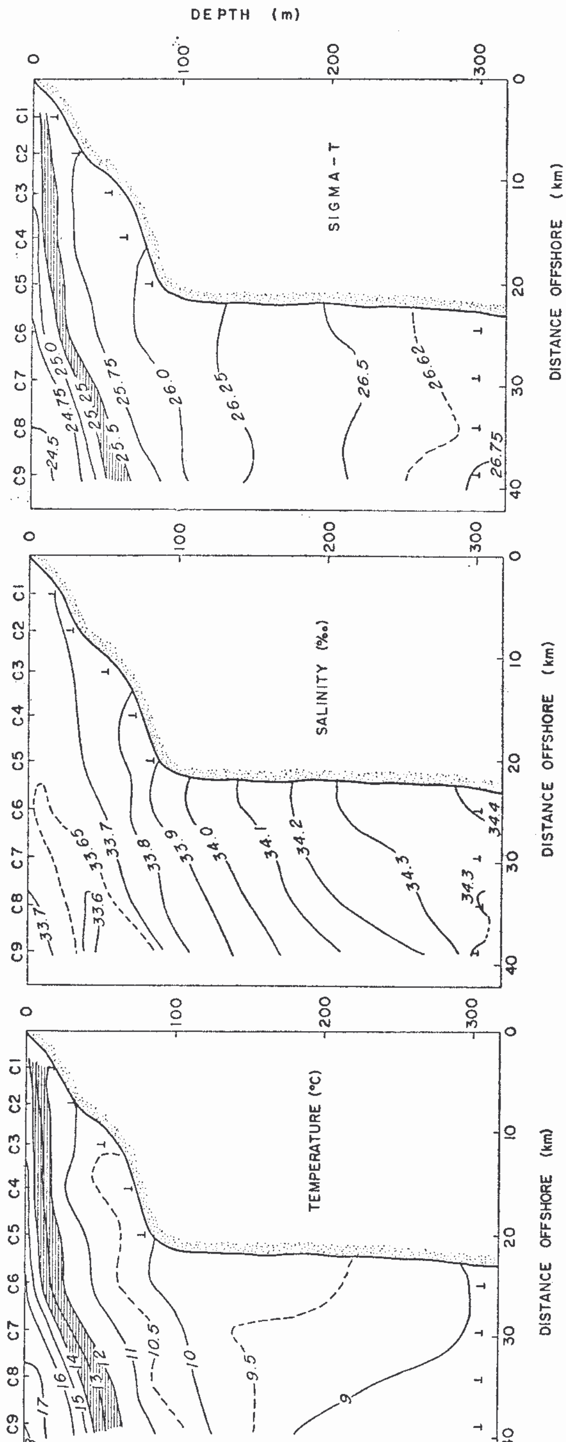

Figure 3. Mean sections of temperature, salinity and sigma-*t* derived by averaging all hydrographic casts at each standard station position on line C. The temperature band $12 < T < 14C$ and the sigma-*t* band $25.5 < \sigma_t < 25.50$ are hatched to facilitate comparison with later figures.

tion 0.75 with wind leading temperature by three days. Temperature-wind correlations for San Jacinto and Los Chichos gave similar results.

A series less frequently sampled in time was the one composed of the occupations of hydrographic line C. Even though less regularly sampled, the sea surface temperature at station Cl, some 5 km offshore showed a similar development to the coastal temperature. The Cl temperatures were lower than any of the shore temperatures and their range of variation was smaller (~ 4 C). Overall, it seemed that the sampling period was one of significant changes in upwelling intensity.

b. Background hydrographic situation. The mean hydrographic fields during the study, along line C (Fig. 3) were derived by averaging all profiles of temperature, salinity and sigma-t at selected depths at each standard station position. Over the shelf, the result was an average of 11 profiles at each site; further offshore, a maximum of five profiles; was available at any position. The most striking features of the temperature field were the shoreward rise of the isotherms above 100 m, most pronounced offshore, and the steeper shoreward descent of the deeper isotherms. The upper 100 m layer offshore was occupied by a salinity minimum which weak-ened towards shore and disappeared over the shelf. Isohalines at all depths tilted up coastward. Because of the weak near-surface salinity stratification, the isopycnals above 100 m closely 'followed the configuration of the isotherms. Below that depth the sigma-t surfaces were more horizontal due to the mutually compensating effects of the temperature and salinity fields.

The shallower uptilting isopleths were interpreted as the combined effect of the equatorward geostrophic flow of the California current and a seasonal mean upwelling maximum in May and June. The descending isotherms and ascending isohalines below 150 m, which defined a core of warmer and saltier water (relative to further offshore) over the continental slope, provided evidence of the northward-flowing undercurrent similar to the results of Wooster and Jones (1970). It was relative to this background or mean situation that the hydrographic variability was interpreted.

c. Variation of the density field. The time series of selected density sections shown in Figure 4 illustrates the temporal development of the upper 150 m of the density field. At the beginning of the hydrographic series on 10 June, the wind strength was weak compared to the preceding and following days. The section of that day, however, was typical of upwelling conditions. All isopycnals sloped upwards towards the coast. The band of isopycnals $25.25 < \sigma_t < 25.50$ (cross-hatched in Fig. 4 for emphasis), broke surface less than 10 km offshore. A thin surface layer of lower density ($< 24.75\ \sigma_t$) was evident over the shelf edge, while on the shelf bottom a layer denser than 26.00 σ_t units extended shorewards to station C2. Despite the decreasing wind strength during the following days, the density field

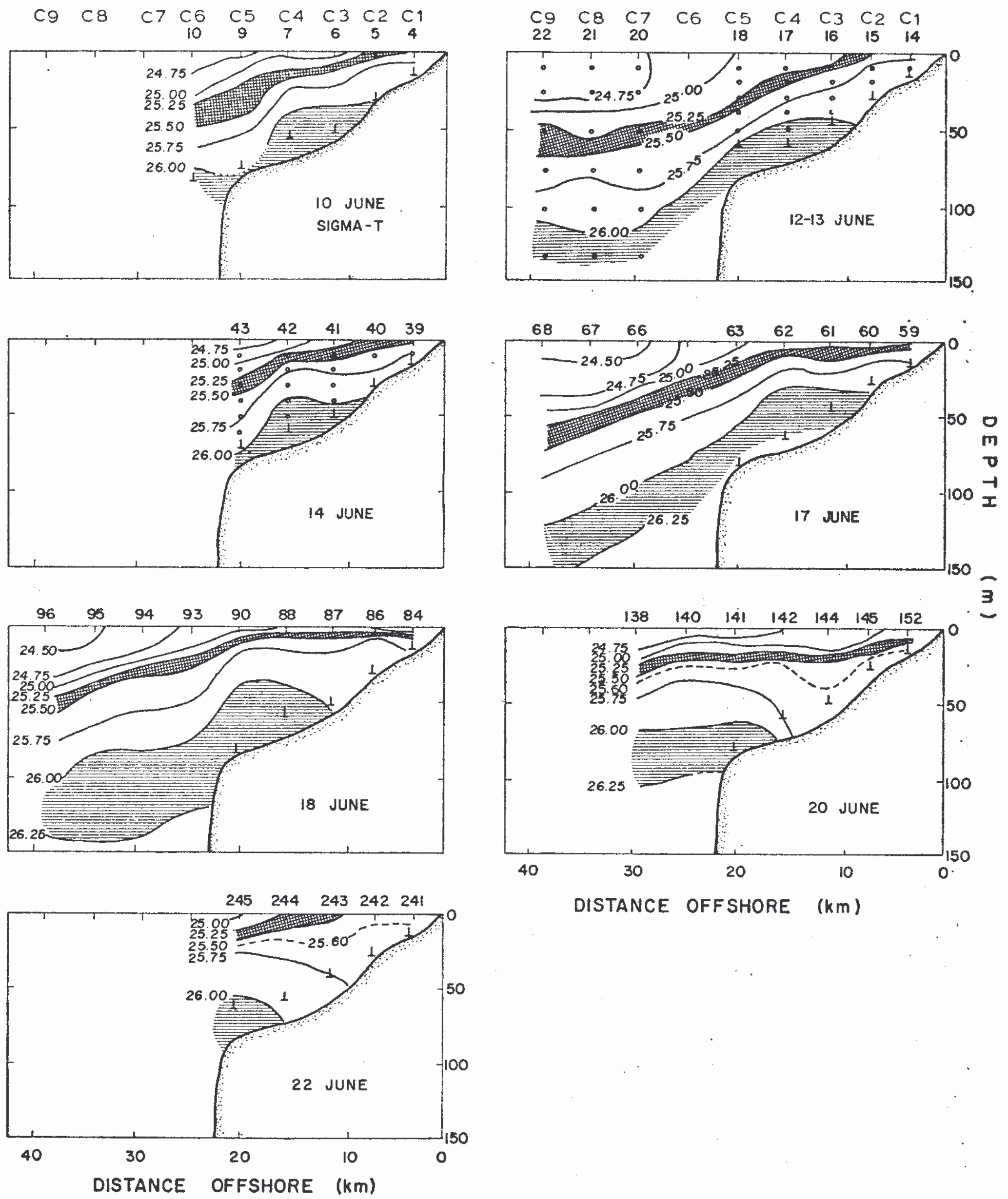

Figure 4. Series of selected sections along line C illustrating time development of the sigma-t field above 150 m. The sigma-t bands of $25.25 < \sigma_t < 25.50$ and $26.00 < \sigma_t < 26.25$ are hatched to facilitate comparison of the sections. Open circles denote depths of subsurface observations with Nansen bottles. An inverted 'T' marks the deepest observation of each cast (where shallower than 150 m) for both Nansen bottle casts and CTD casts.

remained essentially unchanged except that near-surface and nearshore the density decreased gradually as the previously uptilted isopycnals became more horizontal. By 17 June, the sigma-t band 25.25 to 25.50 had submerged completely, apparently because of the continuing weak wind. Paradoxically, the 25.00 isoline at the surface had moved further offshore. No significant change was observed in the position of the 26.00 isoline, which still extended shorewards up the continental shelf. The succeeding hydrographic section, made on 18 June, showed that the 25.25 and 25.50 isosurfaces had sunk further at station C1, so that they were inclined downwards towards shore in the innermost 10 km. Lower density ($\sigma_t < 25.00$) water was apparent at the surface at all stations over the shelf and the 26.00 σ_t surface had retreated seawards down the shelf. These developments occurred despite the strengthening equatorward wind stress.

Even one day later, the section of 20 June made during a period of consistently stronger winds still showed no strong indication of upwelling. Over the shelf edge, surface water of $\sigma_t < 24.75$ had appeared and the 26.00 σ_t surface was situated even further downslope than before. The downslope displacement of this isopycnal was apparently due to increased turbulent mixing over the bottom as it was accompanied by an increase in the thickness of the mid-shelf bottom mixed layer.

Not until 22 June was a marked upwelling response evident, when the sigma-t hand $25.25 < \sigma_t < 25.50$ was seen to break surface again some 10-15 km offshore and deeper waters at the four inner stations had moved shorewards as indicated by an increase in near-bottom density. By the time of this section, the wind stress had actually passed its maximum and was decreasing rapidly in magnitude. Although wind induced vertical mixing apparently occurred, as indicated by the divergence of the 25.50 and 25.75 σ_t surfaces nearshore, the shoreward and upward motion of the 25.75 σ_t surface was consistent with advection due to upwelling nearshore.

d. Density at the anchor station. Between the occupations of the hydrographic line on 20 and 22 June, a 34 hour anchor station of half-hourly CTD casts was main-tained in a depth of 25 m between positions Cl and C2. At this station stratification was initially present (Fig. 5). The density difference between surface and 15 m was 0.55 σ_t units, which corresponded to a temperature difference of 2.67 C. This stratification remained almost constant for five hours and then within a period of 11 hours, the water column became uniform in temperature, salinity and density between the surface and 20 m. The well mixed condition (less than 0.03 C, 0.01^{o}/oo and 0.01 σ_t units difference in the measured water column) persisted for about two hours, until weak stratification (up to 0.3 C, 0.02^{o}/oo, 0.08 σ_t) began to re-appear. The observed transformation from stratified to uniform distributions took place on the day of maximum equatorward wind speed (Fig. 2).

Although the water column became well mixed by downward extension of the surface mixed layer, which was initially less than 5 m deep, it was obvious that

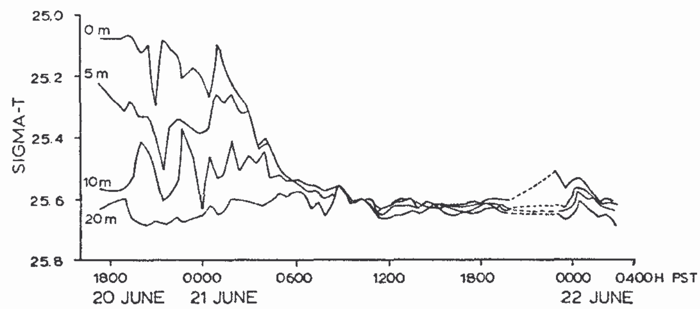

Figure 5. Time variation of sigma-*t* at 0, 5, 10, and 20 m levels at the CTD anchor station. Casts were made every half hour.

the mean temperature and density of the sampled column were changed considerably. The temperature and density at 20 m (5 m above bottom) remained essentially constant throughout whereas the shallower layers became cooler and denser. The possibility that an initially much cooler bottom layer was warmed by mixing during the observation period to conserve the mean properties of the water column was ruled out by a few casts made to within about 2 m of the bottom which indicated little difference between 17.5 m and the bottom.

That the near-bottom temperature and sigma-t remained almost constant despite the vertical mixing, which would tend to increase the bottom temperature and decrease the bottom density, implied that cool, dense water from further offshore was being advected shorewards. This was consistent with the occurrence of upwelling, in which an offshore surface Ekman transport is associated with a deeper onshore compensation flow. No change was appreciable in the 20 m temperature or density at the anchor station because the offshore gradient of these properties was weak near the bottom. Between stations C2 and C3 the differences in deepest observed temperature and sigma-t were only 0.23 C and 0.06 σ_t units, respectively, during the last section previous to the anchor station. The time series observations there-fore support the idea that upwelling was active during the period of strongest winds. Mid-shelf near-bottom water of roughly constant temperature and density was advected shorewards to replace offshore advected surface water and was mixed into the water column nearshore, so reducing temperature and increasing density close to the coast.

e. Profiling Current Meter observations. A time series of hourly Profiling Current Meter casts was obtained from 0900 10 June to 1400 11 June at a mid-shelf site on line C (Fig. 1). The time-depth variation of the alongshore and onshore com-ponents of velocity and temperature is shown in Figure 6. A strong diurnal signal dominated the variability of all three parameters. Maximum alongshore velocities of 80 cm s^{-1} occurred, while the onshore-offshore component was much weaker.

The alongshore flow was generally equatorward and well organized, while the cross-isobath flow alternated between the onshore and offshore directions in a less organized manner. The temperature at 5 m varied by over 2 C during the observation period, while the near-bottom temperature remained virtually constant.

Towards the end of the observation period, from 0500 to 1100 11 June, a pulse of northward flow occurred near-bottom and the bottom mixed layer thickened by a factor of two. The 10.1 C isotherm in Figure *6* defined roughly the upper limit of the bottom mixed layer, which typically varied by less than *0.04* C through its vertical extent. No obvious accompanying occurrence was evident in the cross-shelf flow at that time.

Mean profiles were calculated over the first 24-hour period, along with standard deviation from the mean, and minimum and maximum profiles (Fig. 7). The along-. shore mean flow showed a strong, quite uniform shear (1.3×10^{-2} s^{-1}) between 10 m and 45 m, below which level the mean current speed was almost constant. The onshore-offshore mean flow was weak throughout the water column, especially below 40 m where it was practically zero. From near-surface down, the offshore flow decreased in magnitude, then below 20 m increased to a maximum at 30 m before decreasing again towards zero in a bottom layer. The temperature profiles showed in the mean a roughly uniform depth gradient above a bottom mixed layer below 45 m. That the bottom mixed layer was thicker on occasion was indicated by the minimum profile. Variability of the temperature decreased fairly uniformly with depth but was less than 0.1 C in the bottom mixed layer.

The variation of temperature in the upper layers at the PCM station was about half the magnitude of the temperature variation observed at the shelf stations over the entire experimental period. This relatively large variability was attributable to the position of the station; which coincided with the region where the upwelled iso-lines intersected the sea surface during strong wind periods. Because of the en-hanced offshore gradients associated with upwelling, quite small horizontal displace-ments of the surface waters would be associated with strong temperature and density contrasts. Had the PCM station been occupied during a time of weak or no upwelling; much less variability would have been observed. In fact, four occu-pations of station C3, immediately inshore of the PCM station position, revealed a temperature variation of only ~0.5 C in the near-surface layers over a period of 16 hours on 19 June, when upwelling was not evident.

f. Alongshore structure. The data discussed above were obtained along one line south of the prominent cape of Punta Colonet. On two occasions in June, the grid of stations shown in Figure 1 was occupied. The surface temperature maps (Fig. 8) for 13-14 June, a period of decreasing wind strength, and 17 June, at the end of a week of diminishing wind, show interesting alongshore structure. In the former, a minimum surface temperature of less than 12 C indicated that the thermocline was

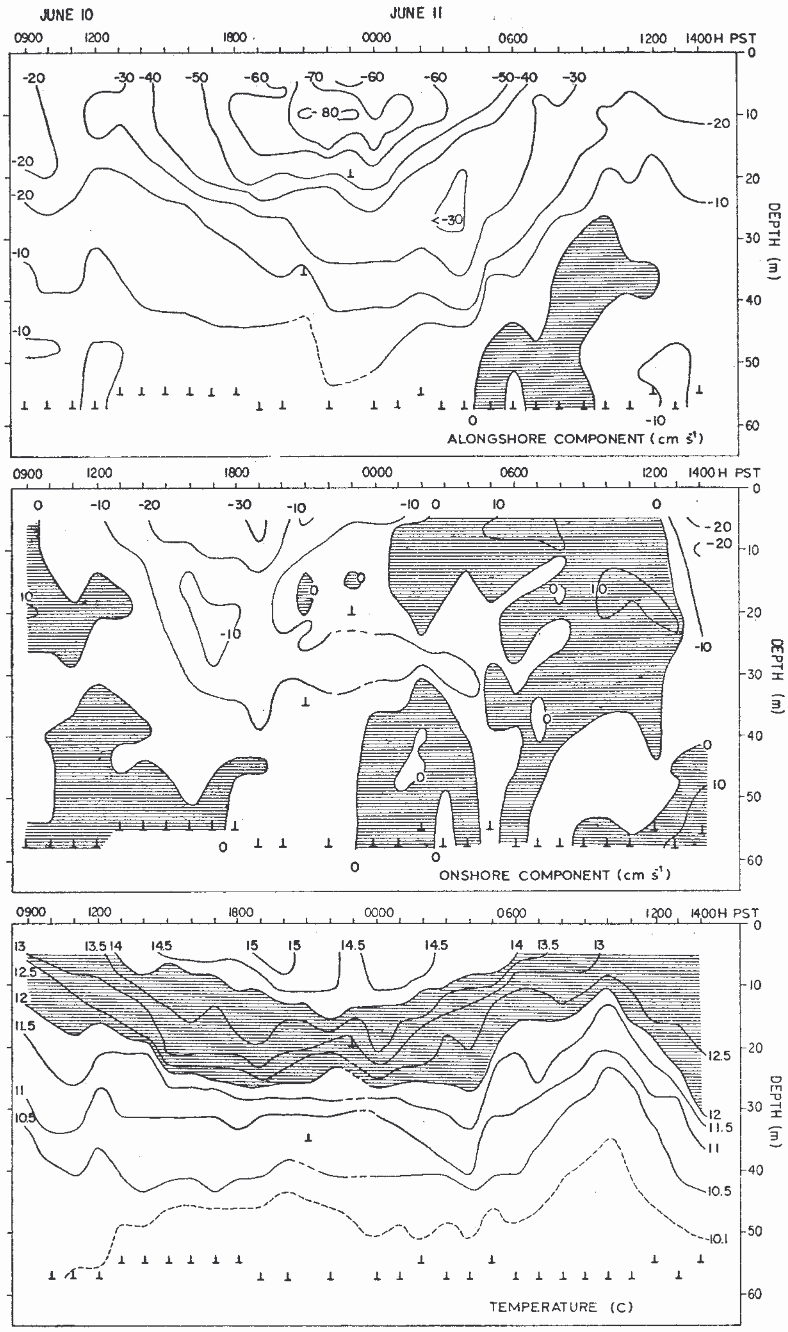

Figure 6. Time-depth plots of alongshore and cross-shelf components of current velocity, and temperature at the current meter anchor station. Casts were made every hour. Shaded flow (positive) is polewards or onshore. The temperature band 12 < T < 14C is hatched to facilitate comparison with other figures. An inverted 'T' marks the deepest observation of each cast.

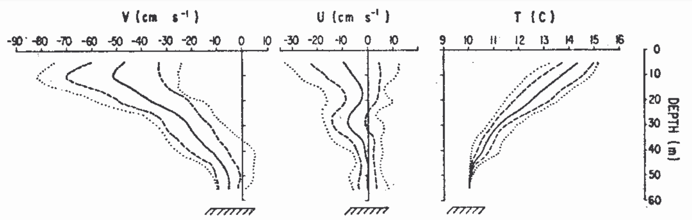

Figure 7. Depth profiles of alongshore and cross-shelf components of current velocity and temperature from the current meter anchor station. Positive flow is polewards or onshore. ———— mean, – – – – – – standard deviation, ... maximum or minimum. The seabed is indicated beneath each profile.

breaking the sea-surface. The coldest location was immediately south of Punta Colonet. In the later map, the minimum surface temperature was a few degrees warmer, consistent with the less intense upwelling indicated by the C-line sections around that time. The coolest site was not immediately south of the cape, but nearshore on line D some 15 km further south. This possibly represented a remnant of the earlier more intense upwelling which was drifting southwards. Some two months before the June study, a series of bathythermograph casts had been made in the area. The surface temperature map (Fig. 8) produced on the basis of that survey showed a similar temperature distribution to that of 13 - 14 June. Water cooler than 12 C was situated south of Punta Colonet, while a tongue-like area less than 13 C spread southwards from the point. The corresponding temperature maps at 10 m and greater depth showed a greater degree of alongshore homogeneity, with isotherms aligned more along the isobaths. The obvious alongshore structure in the surface temperature field suggested that Punta Colonet was producing a local intensification of upwelling and that alongshore advection could be a major influence in the surface layer in the shelf region.

g. Variation in the undercurrent. In Figure 3 it was evident that a nucleus of warmer, saltier water was present within some 20 km of the continental slope at depths greater than about 100 m. This nucleus was identified as northward flowing undercurrent water by comparison of its temperature-salinity characteristics with those of the undercurrent as described by Wooster and Jones (1970). The relevant portions of the temperature-salinity diagrams for all the continental slope and outer stations are shown in Figure 9. The data were broken down into sets corresponding to each standard position.

All the data lay within or close to the range of the data used to illustrate the undercurrent by Wooster and Jones (1970). This range is depicted by the smooth envelope in Figure 9. At station C6, nearest the slope, the layers between 100 m and 300 m always lay close to the high salinity bulge of the envelope, which indicated warmer, saltier water of tropical origin i.e. the poleward undercurrent. In

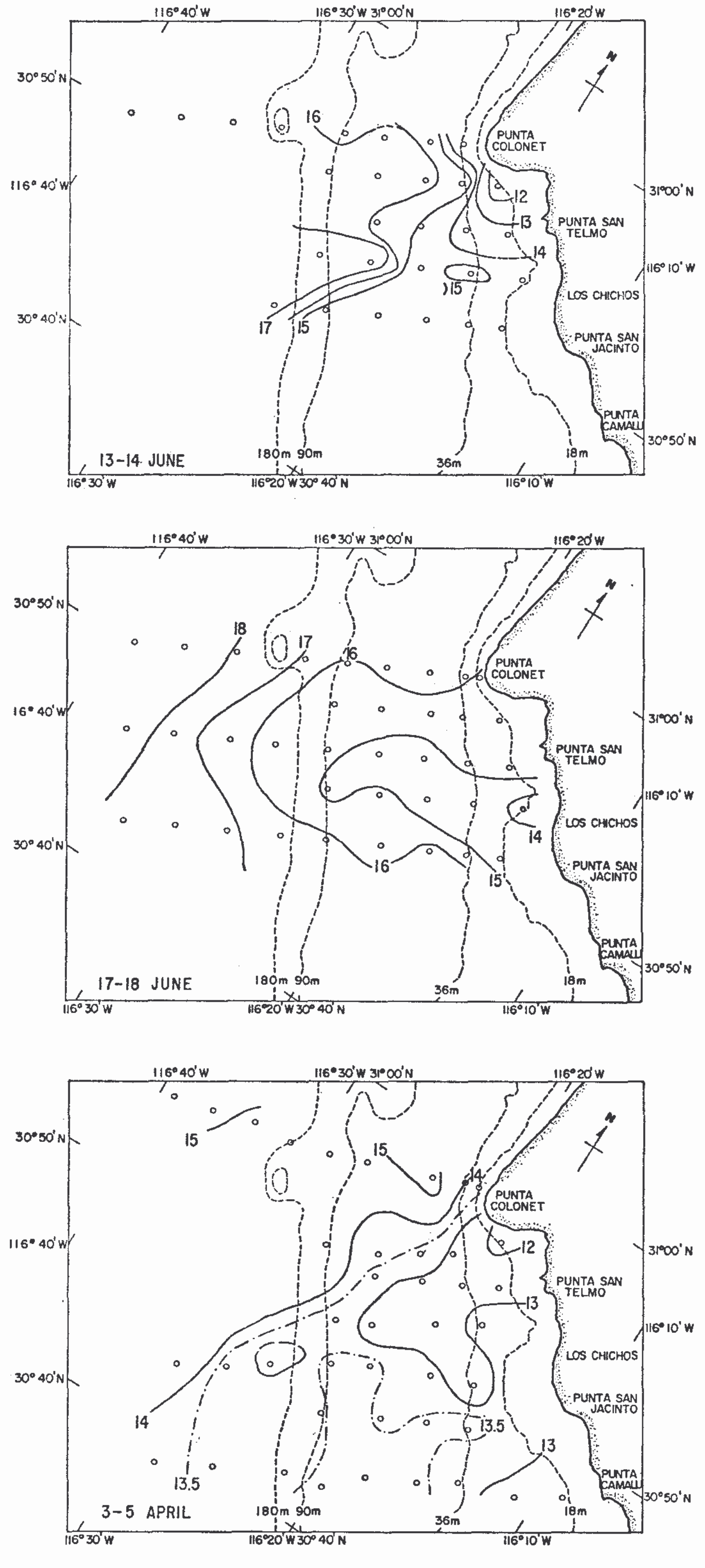

Figure 8. Maps of surface temperature—upper 13-14 June 1976, middle 17-18 June 1976, lower 3-5 April 1976.

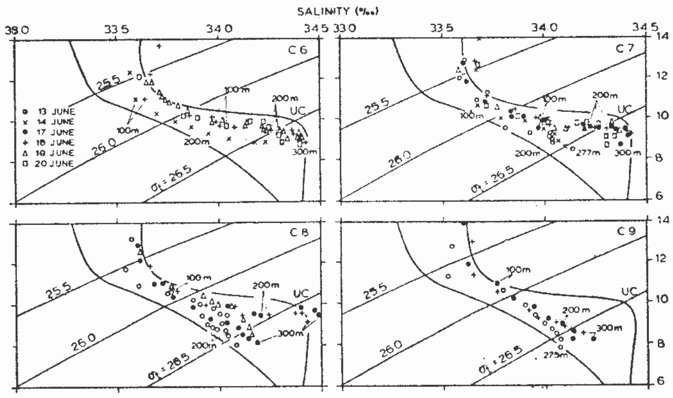

Figure 9. Temperature-salinity diagrams for data at selected depths at the continental slope and offshore stations. Heavy curved lines indicate limits of data used by Wooster and Jones (1970) to illustrate the undercurrent water mass. UC denotes the high salinity, warm water typical of the undercurrent. Light curved lines are of equal sigma-*t*.

contrast, at the outermost station, C9 the characteristics of the deeper layers were on the lower salinity, cooler side of the envelope, i.e. the undercurrent was not present. At the two intermediary stations, C7 and C8, sometimes undercurrent water was detected, sometimes not. At C7, the initial lack of temperature-salinity characteristics typical of the undercurrent indicated that the nucleus of the current was confined to a width considerably less than 10 km on *13* and 14 June, the dates of the earliest samples. Profiles made at this position from 17 June onward indicated that the undercurrent was present, and therefore was wider in extent than previously. At station C8, characteristics of the undercurrent appeared in only two of the profiles made at that position. Their presence at C8 suggested that on late 17 June and 18 June the width of the core of the undercurrent was at least twice as great as on *13* June. (Two profiles were available on 17 June: the earlier one showed no undercurrent characteristics but the later one did). By 19 June, the undercurrent core had shrunk again in width as its characteristics were no longer observed at C8.

While the number of profiles in the undercurrent region was not large, the evi-dence was that considerable variation did occur over a period of days in the width of the identifiable core of the undercurrent. Although no direct measurements exist to definitively associate presence or absence of the identifiable temperature-salinity core to the actual undercurrent, it is likely that the observed variations do reflect fluctuations in the strength of the poleward flow over periods of several days.

4. Discussion

It is evident that the picture of upwelling obtained from the observations was not one of a steady situation. Marked variation in the strength of the low-passed alongshore wind component induced a clear response by the hydrographic fields over the continental shelf. The maximum low-passed equatorward wind strength was over 8 m s^{-1}, which corresponded to a surface wind-stress of about 1.2 dynes cm^{-2}. The latter value was quite low when compared with typical peak values of greater than 2 dynes cm^{-2} observed at coastal wind stations in the Oregon upwell-ing region during the CUE experiments (Huyer, 1976) and in the NW African region during JOINT-1 (Barton et al., 1977).

Sea surface temperature measured at and near the coast and the observed changes in the density field over the continental shelf lagged the wind by about three days. The most pronounced motions of the isopycnals appeared within a distance of 15-20 km of the coast, slightly less than the shelf width. Theoretical understanding of coastal upwelling (O'Brien, 1975; Allen, 1973) indicates that the major vertical motions occur in a narrow coastal zone of typical width equal to the baroclinic radius of deformation (Yoshida, 1955; Charney, 1955). From the present data, this length scale was estimated as about 14 km, which is consistent with the ob-served width of the region of major activity.

An idea of the vertical velocities involved during the upwelling response to the strengthening wind stress, was provided by the vertical displacement of the 25.60 sigma-t surface between 20 and 22 June at the shelf stations. Velocities of 2 x 10^{-8} cm s^{-1} to 9 x 10^{-8} cm s^{-1} were indicated. These were of comparable magnitude to similarly derived vertical velocities from the Coastal Upwelling Experiment Program off Oregon (Halpern, 1976) and from the MESCAL Program near Punta San Hipolito at 27N off southern Baja California (Walsh et al., 1974). Two assump-tions are implicit in the method, namely alongshore invariance of the density field and no mixing across isopycnals. The former was probably valid during the period in question, since the grid occupations indicated the alongshore inhomogeneity was most pronounced at the surface, but the latter was clearly invalid nearshore because of the mixing observed at the time-series station on 20-22 June. However, it was unlikely that such intense mixing occurred at all depths at the deeper shelf stations. Considering only the outer four shelf stations, it was found that estimated vertical velocities were lower at the outer than at the inner stations, consistent with theo-retical ideas.

The time lag of three days which it took for the ocean to respond to the wind seemed somewhat long in comparisonto other upwelling regions, where a time scale of about one day has been observed (e.g., Huyer, 1976). From a simple two-layer transient model, Yoshida (1955) derived an expression for the time needed for the initially horizontal density interface to reach the surface after the onset of upwelling favorable winds. Substitution of representative values from Punta Colonet into his formula provided a time scale of 27 hours, less than the observed one. Because of the gradual nature of the wind variation and the sparseness of the hydrographic sampling, the estimation of response time may have erred towards a higher value.

In contrast to the relatively long response time, the transformation from strati-fied to uniformly mixed conditions at the CTD anchor station was quite rapid. It seems probable that in addition to direct wind stirring from the surface down, turbu-lent mixing due to increased current shear during the period of maximum wind stress contributed to breakdown of the stratified conditions. No current observa-tions were available from the anchor station, but observations in other areas have indicated increased shear in the upper layers as well as an increased barotropic component during periods of stronger wind, e.g., Halpern (1976). The region of complete surface-to-bottom mixing probably did not extend much further out from the coast than the anchor station position. At least, by 22 June about 12 hours after the anchor station the water column was density stratified at stations offshore of C2.

A completely mixed nearshore zone has not been reported in the Oregon up-welling region, but during the JOINT I experiment off Northwest Africa it was observed that the water column over the continental shelf was vertically homo-geneous as far as 40 km from the coast during the periods of most intense wind (Barton *et al.*, 1977). The extent of the vertical mixing is related to the density stratification and wind stress. Off Northwest Africa, the stratification was weaker than off Oregon or Baja California and the wind stress was greater (Huyer, 1976). The stratification was strongest off Oregon, where vertical mixing is apparently in-hibited despite a greater wind stress than observed off Baja California.

The various grid occupations showed that the coastal promontory at Colonet had an appreciable effect on the surface distributions but little at depth. Since the cape is a much smoother feature below surface, even at 20 m (Fig. 1), it is not surprising that the sub-surface distributions are more homogeneous alongshore. One of the possible mechanisms which might enhance upwelling near capes is downstream divergence of the flow. However, it was notable that Punta Colonet, an impressive cliff over 100 m high in many parts, effectively blocked out the wind for a short distance downwind. There was therefore a strong zonal gradient in the alongshore wind component between the calm, sheltered region inshore and south of the point and the exposed area beyond the point. A wind induced diver-gence in the Ekman transport of this type might also have produced a localized upwelling near the cape. In this case, the upwelling would vary with wind strength and direction.

The depth influenced by the variation of the wind was apparently fairly limited. The changes below the surface layer and beyond 15 km from shore were relatively weak. No evidence of a bottom layer of shoreward transport of cooler denser water as reported by Johnson *et al.*, (1975) off Northwest Africa, was found. During the short current meter time series the cross-shelf flow near bottom was very weak and with a mean close to zero.

In the co-ordinate system aligned with the overall lie of the isobaths, the mean cross-shelf flow was offshore above 40 m and almost zero below that. With a clock-wise rotation of 6 degrees it was possible to produce a mean cross-shelf profile with a 15 m sub-thermocline layer of onshore flow of up to 5 cm sec^{-1} between an upper and lower offshore flow. Although cross-shelf flows with more than one cell have been observed elsewhere with several day deployments of profiling devices similar to the one used in this study (Johnson *et al.*, 1975; Johnson *et al.*, 1976; Mooers *et al.*, 1976), they have never been observed with fixed-level current meter arrays, e.g., Halpern (1976), Halpern *et al.*, (1977). Since the Punta Colonet data represented only one day at a particular site in an apparently changeable situation, the observed profile certainly cannot be definitive.

The mean alongshore velocity profile was similar in overall characteristics to profiles observed off Oregon e.g., Johnson *et al*., (1976). The strong diurnal signal observed in the current was enhanced by contributions due to the seabreeze regime and inertial currents. A longer time series would be needed to discriminate between the various influences.

The appearance of near-bottom northward flow during the profiling series indicated that the poleward undercurrent penetrated at least at times into the outer and mid-shelf regions. Since the upper limit of the nucleus of typical undercurrent water was about 100 m both in this study and in the one by Wooster and Jones (1970), this seems reasonable. More notably, the evidence was that significant changes occurred in the width and, presumably, strength of the undercurrent over a period of days. If the undercurrent actually does reach onto the continental shelf, then fluctuations over the slope will exert an influence on the upwelling system by introducing different amounts of the distinct undercurrent water mass into the upwelling cycle. The undercurrent therefore represents an additional source of variability to the shelf waters.

The Colonet study provided a first look at the upwelling which governs northern Baja California coastal waters. It was found that the variation in the alongshore wind component excited a response in the hydrographic fields. The effective width of the upwelling zone and the deduced vertical velocities were in accord with simple theoretical predictions and observations in other regions, although the response time was rather long. The prominent cape at Colonet clearly was instrumental in producing a surface plume of colder water downstream, but at 20 m depth its effect was undetectable. The alongshore current structure appeared similar to that found off Oregon, while the cross-shelf flow was relatively poorly organized. The high salinity core of poleward undercurrent over the slope varied in width by a factor of two over a few days.

Obvious lines of further investigations are the determination of the alongshore and cross-shelf current regimes and their variability, the measurement of the under-current and its relation to the temperature-salinity characteristics, and investigation of the relationships between currents, hydrography, sea-level and winds. A program of current measurements off Baja California is presently underway which should provide some insight into these problems.

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