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Poleward Flow off Central California During the Spring and Summer of 1981 and 1984

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Currents and winds measured over the continental shelf and upper continental slope during the first half of 1984 are analyzed to determine the character of the flow off central California (Point Conception to San Francisco). The mean flow was poleward from Point Conception to Point Sur, in opposition to the equatorward wind stress. The mean flow was equatorward north of Point Sur. Fluctuations in alongshore currents over the shelf were highly correlated with local winds everywhere except off Point Conception, where currents were not only uncorrelated with wind but also poorly correlated with currents farther north. North of Point Buchon there is evidence for poleward propagation of shelf current variability at 175–200 cm/s. The correlation between currents and local wind forcing dropped considerably beyond the shelf break, only 10–15 km offshore from the shelf moorings. During extended periods of weak equatorward winds, the poleward shelf flow south of Point Sur spreads farther offshore over the continental slope. A three week period of calm winds in July 1984 resulted in a 100-km-wide tongue of poleward flow extending 300 km along the California coast. Similar, but somewhat weaker, poleward surface flow occurred during the same period in 1981; a 2- to 3-week period of calm winds in late June and early July 1981 resulted in a 100-km-wide tongue of poleward flow extending at least 150 km along the California coast. In contrast to the poleward flow on the shelf, which appears to be normal during spring and summer, the poleward surface flow observed over the slope in July 1981 and 1984 is unusual, based on historical hydrographic surveys off the central California coast. Poleward surface flow over the continental slope occurs seasonally in the winter but is not generally observed after February.

1. INTRODUCTION

On the basis of historical hydrographic data collected since 1949 by the California Cooperative Oceanic Fisheries Investigations (CalCOFI), poleward directed currents are expected over the continental slope along the central California coast in the October–February period; this seasonal flow is referred to as the Davidson Current [*Sverdrup et al.*, 1942; *Reid and Schwartzlose*, 1962; *Hickey*, 1979; *Chelton*, 19841. The nearshore poleward flow over the slope normally reverses in spring when the equatorward directed winds increase. Poleward surface currents in this season are relatively uncommon over the slope, as is indicated by climatological maps of dynamic height and geostrophic velocity [*Wyllie*, 1966; *Hickey*, 1979; *Chelton*, 1982; *Lynn and Simpson*, 1987]. This seasonally reversing pattern of surface flow (Figure 1) is most pronounced along the central California coast, extending about 100 km offshore in the upper 100 m of the water column. Below this depth level, flow tends to be more persistently poleward (Figure 1) and is generally referred to as the California Undercurrent.

There have been few long-term current meter moorings or high-resolution hydrographic surveys inshore of the continental shelf break along the central California coast. Consequently, less is known about seasonal variability or spatial coherence of the flow over the shelf in this region. As part of a recently completed field measurement program sponsored by the Minerals Management Service (U.S. Department of the Interior), currents, winds, hydrography, and drifter trajectories were measured off the central California coast for the 18-month period from February 1984 through July 1985. A summary of the components of this experiment, called the Central California Coastal Circulation Study (CCCCS), is given by *Chelton et al.* [1987]. The objective of CCCCS was to obtain a detailed description of the circulation (including seasonal variability) on the continental shelf and upper continental slope between Point Conception and San Francisco (Figure 2). This paper focuses on the first 6 months of near-surface (70 m) CCCCS current measurements. An analysis of deeper currents and the complete 18-month data set is presently in progress.

Evidence presented in this paper, based on current meter measurements, satellite sea surface temperature (SST) imagery, buoy drift trajectories, and hydrographic data, indicates very strong poleward surface flow over the continental slope and shelf from Point Conception to Point Sur in June and July 1984. From the limited historical current meter data it appears that poleward flow on the shelf is normal along the central California coast. However, the strong poleward surface flow beyond the shelf break marks a significant departure from the conventional picture of seasonal circulation off central California. This paper presents a detailed description of this unusual event in 1984 and compares it with similar data from 1981 and the seasonal norm as determined from historical CalCOFI hydrographic measurements.

2. MOORED MEASUREMENTS OF WINDS, CURRENTS, AND TEMPERATURE

1984 Observations

During the first half of 1984, surface wind measurements were obtained from three National Data Buoy Center (NDBC) buoys along the central California coast (Figure 2). The raw data consisted of hourly observations. These were low pass filtered with a half-power point at 4 days and subsampled at 6-hour intervals. The principal axes of wind stress at these buoys are given in Table 1. Wind stresses were estimated from observed vector winds using the bulk aerodynamic formula with the *Large and Pond* [1981] wind speed

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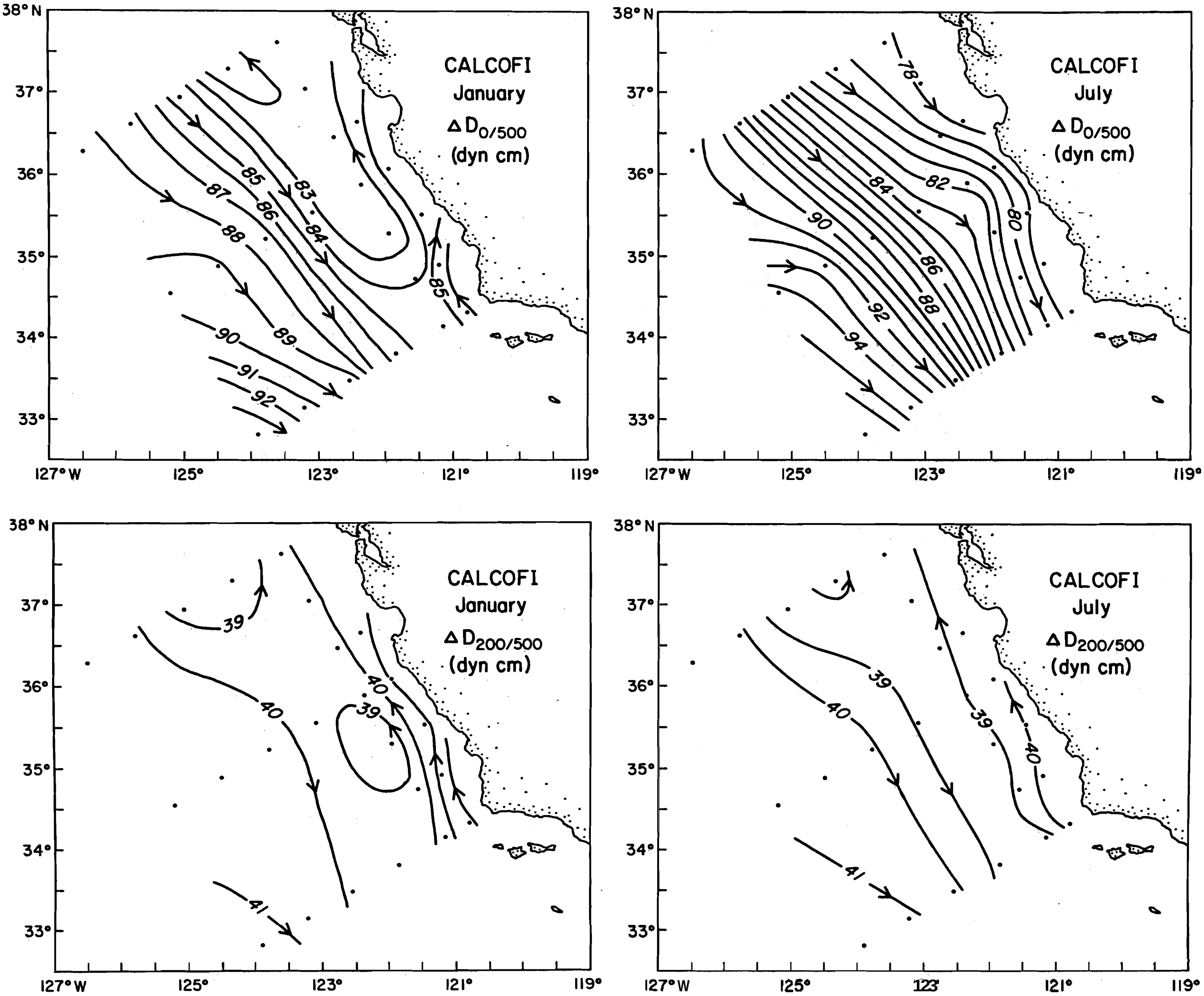

Fig. 1. Seasonal average January and July dynamic heights of the sea surface and 200 dbar relative to 500 dbar off the central California coast. Seasonal averages were determined by harmonic analysis of CalCOFI hydrographic data as described by *Chelton* [1984].

dependent drag coefficient (extended from a lower limit of 4 m/s to 0 m/s). The alongshore coherence length scales of the wind field off central California are large (see Figure 3); the cross correlations between wind stress measured at the three buoys are about 0.8 and occur at zero lag in all cases (Table 2). The time series of alongshore wind stress for buoy 46011 off Purisima Point is shown in Figure 4*a* for the period February through July 1984. With the exception of three calm periods between the last week of February and the middle of March and another calm period in early April, equatorward winds increased steadily from February through May. The winds then steadily decreased during May and June. For the first 3 weeks of July, the winds were very weak. Equatorward winds began to increase again the last week of July.

Water temperature was measured near the surface (2-m depth) at buoy 46011 and at 70 m at nearby CCCCS mooring site C (Figures 4*c* and 4*d*, respectively). The raw hourly observations were low-pass filtered and subsampled like the wind data. Consistent with the general steady increase in equatorward winds over the period February through May, SST decreased from about 14°C to 10.5°C. In June and July, episodes of zero or weak equatorward winds were followed within a few days by marked increases in SST. This simple relation between winds and coastal SST is expected from the classical picture of coastal upwelling [*Smith*, 1968; *Brink*, 1983]. The temperature at 70 m followed the same general pattern of decrease (though with smaller range) over the period February through May 1984. In late April 1984, 70-m temperature dropped suddenly from about 10°C to 9°C. This probably marks the occurrence of the 1984 spring transition [*Huyer et* al., 1979; *Strub et* al., 1987*a*; *Lentz*, 1987] off central California. This signal was only weakly apparent in SST at buoy 46011 but was very evident in both SST and 70-m temperature at NDBC buoy 46028 and CCCCS site F farther north (see dashed lines in Figures 4*c* and 4*d*).

During June, both SST and 70-m temperature varied in response to the fluctuating equatorward winds. Subsequent to the 3-week period of light winds in July, SST increased by over 4°C. The 70-m temperature over the shelf increased by about half that amount over the same period. These signals are evident at both sites C and F (Figure 4*d*). Such temperature changes at depth could be caused either by poleward advection of warm water or by changes in cross-shore isotherm slope (deepening nearshore) associated with geostrophic adjustment of the poleward flow in response to weakening equatorward winds.

Currents were measured at 11 locations along the central California coast in the CCCCS field study (Figure 2). At each mooring location, current meters were installed at nominal depths of 10, 30, 70, 220, and 470 m. Shelf and upper continental slope moorings were placed approximately over the 100-m and 250-m isobaths, respectively. Measurements of current velocity at depths shallower than 70 m were lost owing to a variety of problems [see *Chelton et al.,* 19871. Consequently, the nearest surface current measurements from CCCCS were at a depth of 70 m. These 70-m currents are analyzed in this study. Hourly observations were low pass filtered and subsampled at 6-hour intervals like the wind and temperature data. The time series of 70-m alongshore currents for the midshelf current meter at site C near wind buoy 46011 is shown in Figure 4b. With the exception of two periods of substantial equatorward flow in April and another in early June, the alongshore velocity was generally poleward throughout this 6-month period with typical speeds of 10–20 cm/s. Particularly strong poleward flow generally occurred within about a day of a slackening in the equatorward winds.

The alongshore and cross-shore components of 70-m currents at each of the four CCCCS shelf moorings along the 100-m isobath are shown in Figure 5. The poleward flow observed at site C appears to be characteristic of shelf currents between Point Conception and Point Sur. At the three southern moorings, the alongshore flow was generally poleward, with almost exclusively poleward flow at site F. Poleward flow was in excess of 30 cm/s in late July at site F following the 3-week period of weak winds. At the northernmost shelf mooring (site K), the flow was generally equatorward. Mooring H placed on the shelf off Point Sur was unfortunately lost early in the field program. However, except for a 2-week period in April, alongshore 70-m current velocity 5.2 km farther offshore at site J was poleward through most of the first half of 1984 (see Figure 6). (This cross-shore separation is less than half that of any of the other shelf-slope mooring pairs; see Table 4.) It therefore seems likely that currents over the shelf off Point Sur were also poleward during this period. This would imply a strong flow convergence between Point Sur and CCCCS site K, which would lead to offshore flow. Such offshore flow north of Point Sur can indeed be inferred from hydrographic and satellite measurements as discussed in sections 4 and 5.

TABLE 1. Major Principal Axes of Wind Stress Determined From the February–July 1984 Time Series at Three NDBC Buoys off the Central California Coast

Wind Buoy	Major Axis, °T
46012	331.8
46028	311.4
46011	318.3

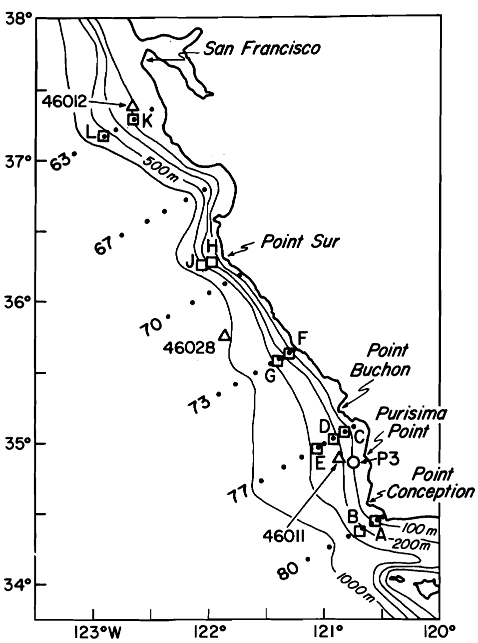

Fig. 2. Map of the central California coastal region. NDBC wind buoys are shown by triangles, CCCCS current meter moorings (labeled A through L, excluding I) are shown by squares, and the Super-CODE mooring P3 is shown as a circle. The dots indicate the locations of the large-scale array of CCCCS conductivity-temperature-depth (CTD) stations with line number labels corresponding to the standard CalCOFI line numbering convention.

The CCCCS current meter data set offers an opportunity to examine quantitatively the relation between shelf currents and winds over a 370-km stretch of the central California coast. The maximum correlations and corresponding time lags between currents at CCCCS shelf mooring sites A, C, F, and K and the alongshore wind stress measured at the nearest buoy locations to the south are given in Table 3. Currents at site A off Point Conception were unrelated to local wind forcing. Farther north, current fluctuations were more highly correlated with winds, with maximum correlations of 0.61, 0.61, and 0.73 at sites, C, F, and K, respectively, at lags of 0 to 0.5 days. The similarity between correlations with wind stress at these three current moorings may seem somewhat surprising. As noted previously from Figure 5, the mean alongshore flow at site K was opposite that at sites F and C. However, correlation analysis indicates that much of the variability about these means can be explained by local wind forcing (53% of the variance at site K and 37% of the variances at sites C and F). Similar correlation values and lags of maximum correlation between wind stress and currents over the shelf have been found off northern California in the Coastal Ocean Dynamics Experiment (CODE) [*Winant et al.,* 19871, where winds are comparable in strength to those off central California.

The lack of coupling between winds and shelf currents off Point Conception is rather interesting. The different nature of the circulation in the region just north of Point Conception is further illustrated by drifter trajectories as discussed in section 5 (see Figure 19). Drifters tended to wander in the southern portion of the field study region but moved rapidly poleward once north of Purisima Point. It has previously been shown [*Chelton,* 1984; *Brink and Muench,* 1986] that currents in the region near Point Conception are strongly influenced by flow into and out of the Santa Barbara Channel to the south and east. This flow is apparently not related in any simple way to local wind forcing or to currents north of Point Conception.

The high correlation between wind stress and currents observed over the shelf north of Point Conception drops considerably beyond the shelf break (Table 3). The correlation

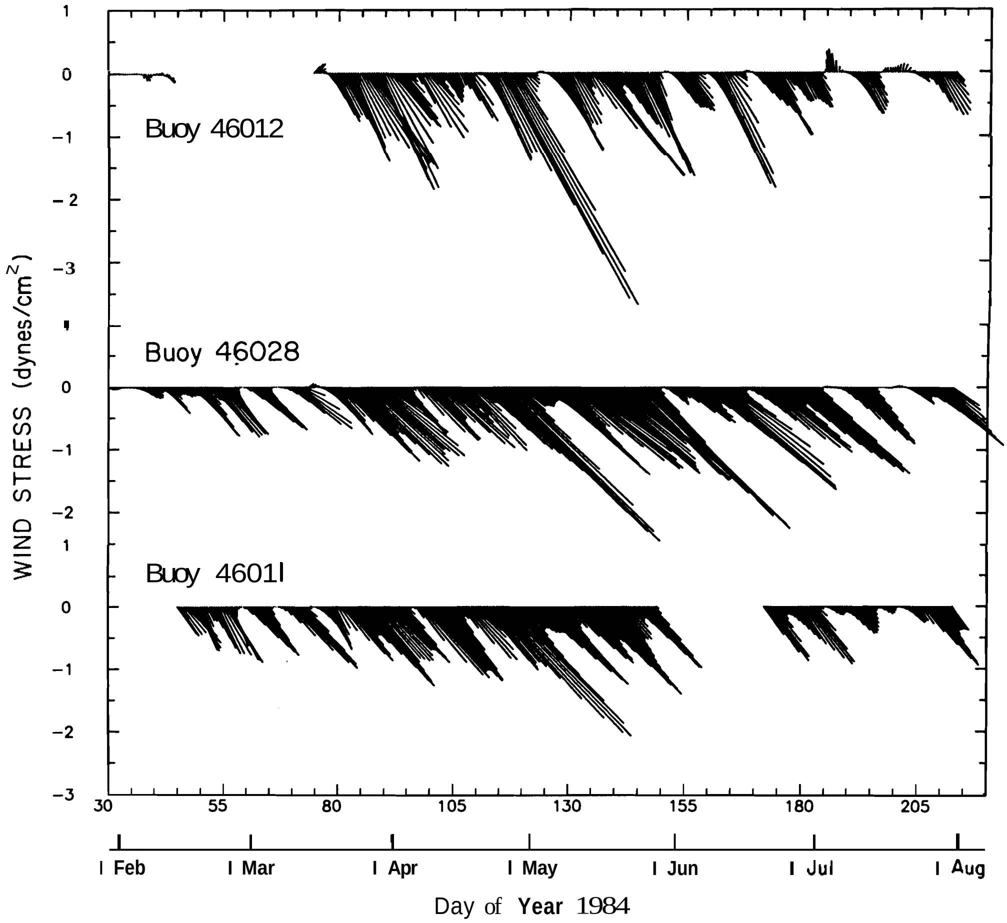

Fig. 3. Stick plot of vector wind stress measured over the period February–July 1984 at the three NDBC buoys shown in Figure 2. Sticks point toward the direction the wind was blowing, and the length of the sticks indicates the magnitude of the wind stress (scale on left axis).

between wind stress and 70-m slope currents is not statistically significant at site B off Point Conception. North of Point Conception, local wind forcing accounts for only 10–19% of the variability in slope currents. This represents a threefold decrease from the correlations between wind stress and currents measured at neighboring shelf moorings typically located only 10–15 km closer inshore. *Winant et al.* [1987] also found that currents over the upper continental slope off northern California were poorly correlated with local wind forcing. The 70-m current time series at the CCCCS upper continental slope moorings along the 250 m isobath are shown in Figure 6. Consistent with the lower correlation between slope currents and winds, there was less current variability over the slope than over the shelf on the 3- to 10-day time scales typical of the wind field. This is evident visually from Figures 5 and 6 and is shown more quantitatively in the spectra of alongshore wind stress and shelf and slope currents in Figure 7. The correlations between upper slope currents and nearby shelf currents are given in Table 4. Shelf currents separated by as much as 220 km alongshore were as highly correlated as shelf and upper slope currents separated by only 10–15 km cross shore. The alongshore currents beyond the shelf break may be correlated with the low-frequency components of wind forcing, but the 6-month data set analyzed here is too short for frequency domain analysis. This question will be addressed from analysis of the full 18-month CCCCS data set.

Besides local wind forcing, variability of shelf currents should also be related to poleward propagation of coastal trapped waves. The cross correlations between alongshore currents at the four CCCCS shelf moorings are given in Table 4. The currents at site A are only weakly correlated with currents at site C (correlation of 0.32) and are essentially unrelated to currents farther north. At mooring sites F and K, the cross correlations with currents at neighboring stations are high (0.61 and 0.57, respectively). Part of this correlation may, however, be an indirect result of the high correlation between alongshore currents and local wind stress at each mooring as discussed previously and given in Table 3.

TABLE 2. Maximum Cross Correlations and Corresponding Time Lags Between Alongshore Wind Stress Measured at Three NDBC Buoys off the Central California Coast

Buoy Pair	Maximum Correlation	Variance Explained, %	Lag of Maximum Correlation, days
46012, 46028	0.82	67	0
46012, 46011	0.78	60	0
46028,46011	0.79	62	0

The 95% significance level (computed as by *Chelton* [1983]) is about 0.20 in all cases. Alongshore direction is defined by the major principal axes of vector wind stress given in Table 1.

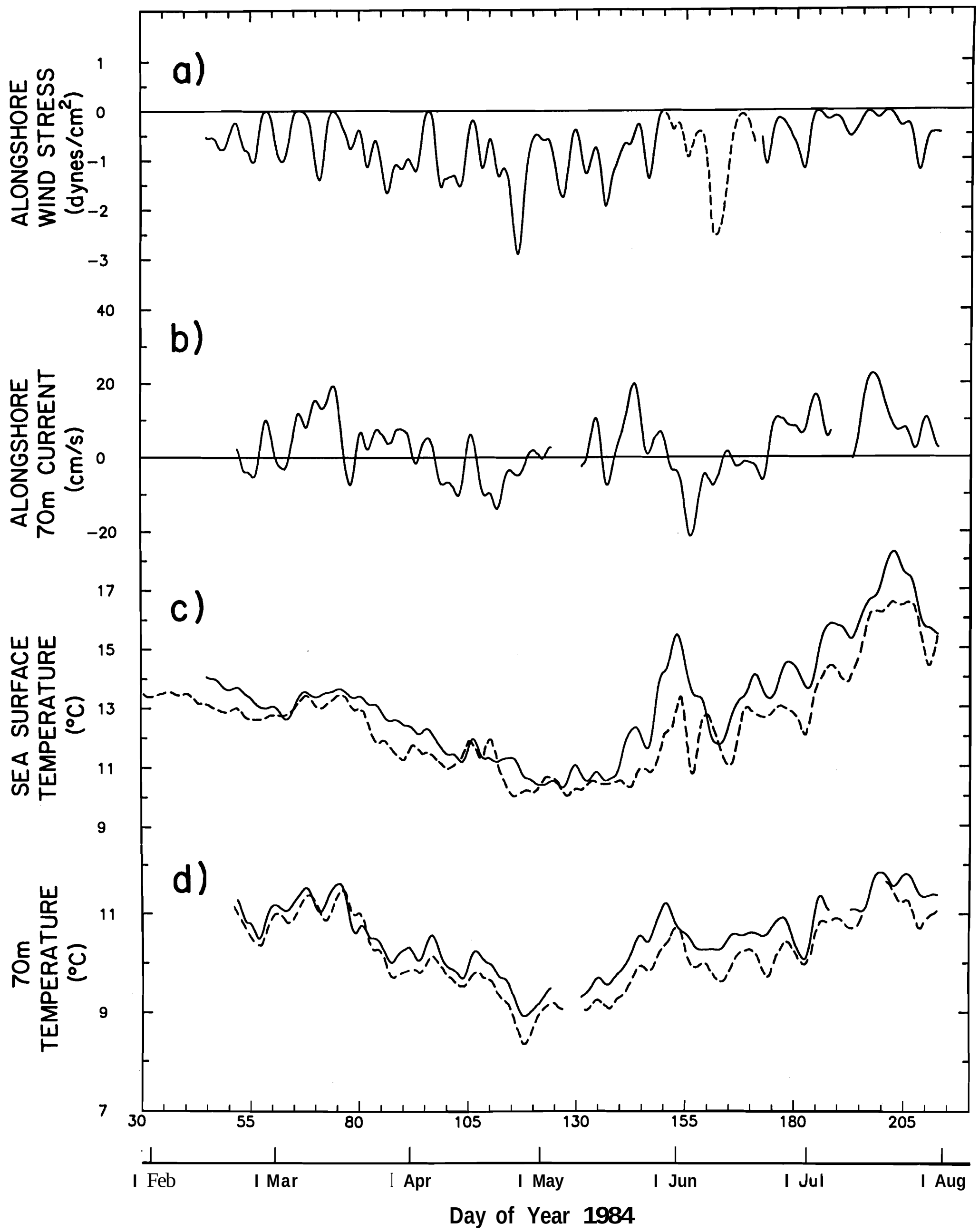

Fig. 4. Time series measurements for the period February through July 1984 of (a) alongshore wind stress at buoy 46011 (the dashed line in the data gap during the first half of June is the wind stress at buoy 46028, 119.5 km to the north); (b) alongshore currents at 70 m at CCCCS site C, (c) sea surface temperature (SST) at buoy 46011, and (d) 70-m temperature at site C. The alongshore direction for winds and currents is defined to be the principal axes determined from the 6 months of data (Tables 1 and 3), with positive values poleward. Dashed lines in Figures 4c and 4d are SST at buoy 46028 and 70-m temperature at CCCCS site F, respectively.

The effects of local wind forcing and poleward propagation can be separated to some degree by multivariate regression of alongshore shelf currents at each mooring site on local alongshore wind stress and alongshore shelf currents at the neighboring mooring site to the south. At all shelf mooring sites, the lag between alongshore current and local alongshore wind stress was fixed at 0.25 day in the multivariate regressions. The lag between alongshore current and alongshore current to the south was varied from -1 week to $+1$ week. The maximum correlations and corresponding lags are given in Table 5 for shelf mooring sites C, F, and K. The increases in percent variance explained over the simple correlation with local wind stress are modest at sites K and F (8% and 16%, respectively) but statistically significant. The 1.25-day and 0.5-day lags of these correlations correspond to poleward propagation at speeds of 205 and 174 cm/s. These propagation speeds are 20–30% slower than model estimates for first-mode coastal-trapped waves [*Battisti and Hickey*, 1984; *Denbo and Allen*, 19871. Using realistic bathymetry and density stratification for California coastal waters, *Chapman* [1987] estimated poleward propagation speeds of 160–190 cm/s for the second-mode coastal-trapped wave, which is more consistent with the

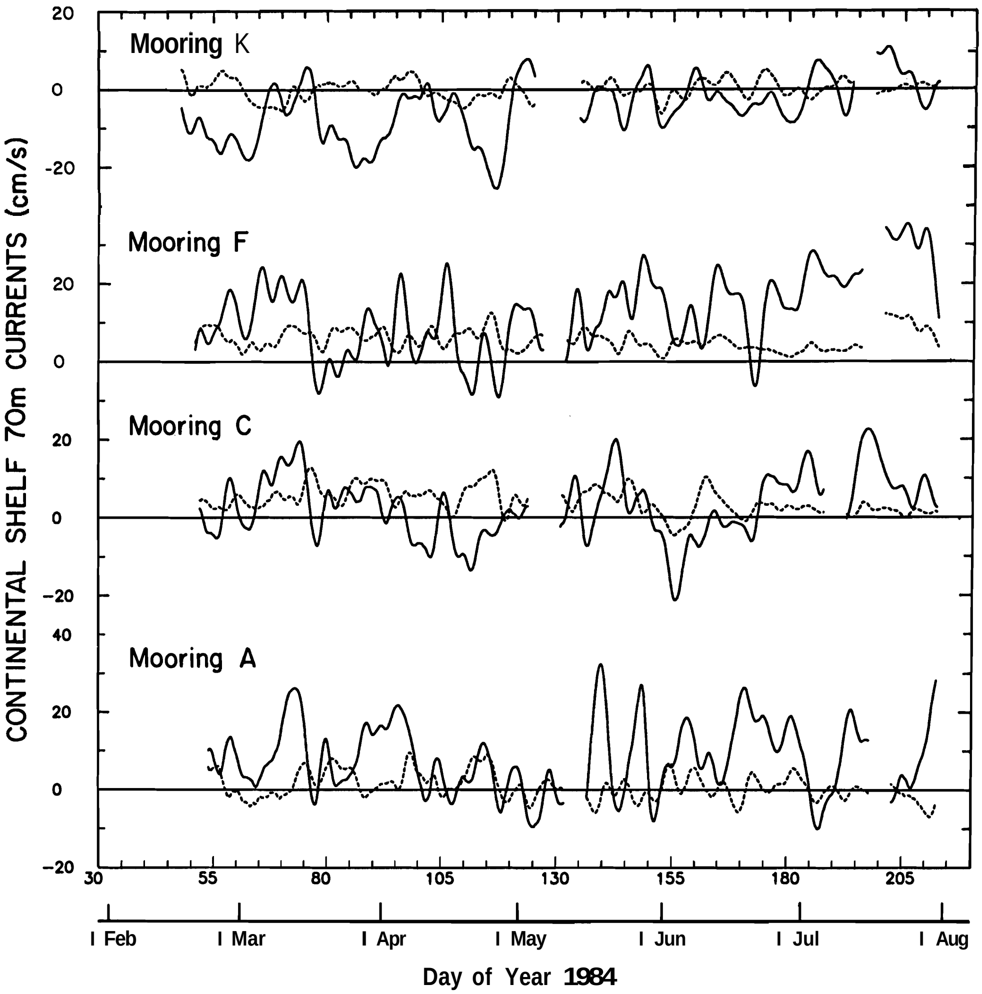

Fig. 5. Alongshore (solid lines, positive poleward) and cross-shore (dashed lines, positive onshore) currents at 70 m over the continental shelf at CCCCS moorings A, C, F, and K (the mooring at site H was lost) for the period February–July 1984. Alongshore and cross-shore directions at each site were defined by the principal axes determined from the 6 months of data (Table 3).

observed lags in Table 5. The increase in variance explained at site C is not statistically significant, indicating that variability in shelf currents at site C is related to local wind forcing but not to currents at Point Conception to the south.

Though it is rather difficult to separate local wind forcing and poleward propagation, we conclude that most of the explained variance of alongshore shelf currents north of Point Conception is most likely due to local wind forcing. North of Point Buchon, the contribution of poleward propagation to shelf current variability is also significant, though smaller than local wind forcing.

1981 Observations

During 1981, similar surface wind and shelf current measurements are available near 34.8°N for comparison with the 1984 CCCCS data at nearby site C. The alongshore wind stress at NDBC buoy 46011 during the first half of 1981 is shown in Figure 8*a*. There was a brief period of substantial poleward wind stress during late February and early March. Thereafter, the alongshore component of wind stress remained equatorward through July, fluctuating between zero and 1.5 dyn/cm^2. There were several periods of light winds, most notably in mid-June, when the alongshore wind dropped to zero for 5 days, increased to about 0.75 dyn/cm^2 equatorward for about 5 days, and then dropped again to near zero for about 2 weeks. There were two moderate equatorward wind events of about 1 dyn/cm^2 in mid-July, followed by very light equatorward winds for the last 2 weeks of July.

Current and temperature measurements were made in 1981 over the shelf off the southern portion of the central California coast near buoy 46011 as part of a large-scale component of CODE, called SuperCODE [Denbo and Allen, 1987; *Strub* et al., 1987*b*]. Near-surface (2-m depth) temperature at buoy 46011 is shown for the period February through July 1981 in Figure 8*c*. Temperature at 70-m depth at SuperCODE mooring P3 off Purisima Point (see Figure 2) is shown in Figure 8*d*. The seasonal development of the temperature field during 1981 was very similar to 1984; the general trend was a decrease in temperature over the first 4 months. The 70-m temperatures dropped suddenly from 11.5°C to 9.5°C in late March. This coincides with the time of occurrence of the 1981 spring transition off northern California [Lentz, 19871. As with the 1984 data, this signal was not as clearly present in SST at buoy 46011.

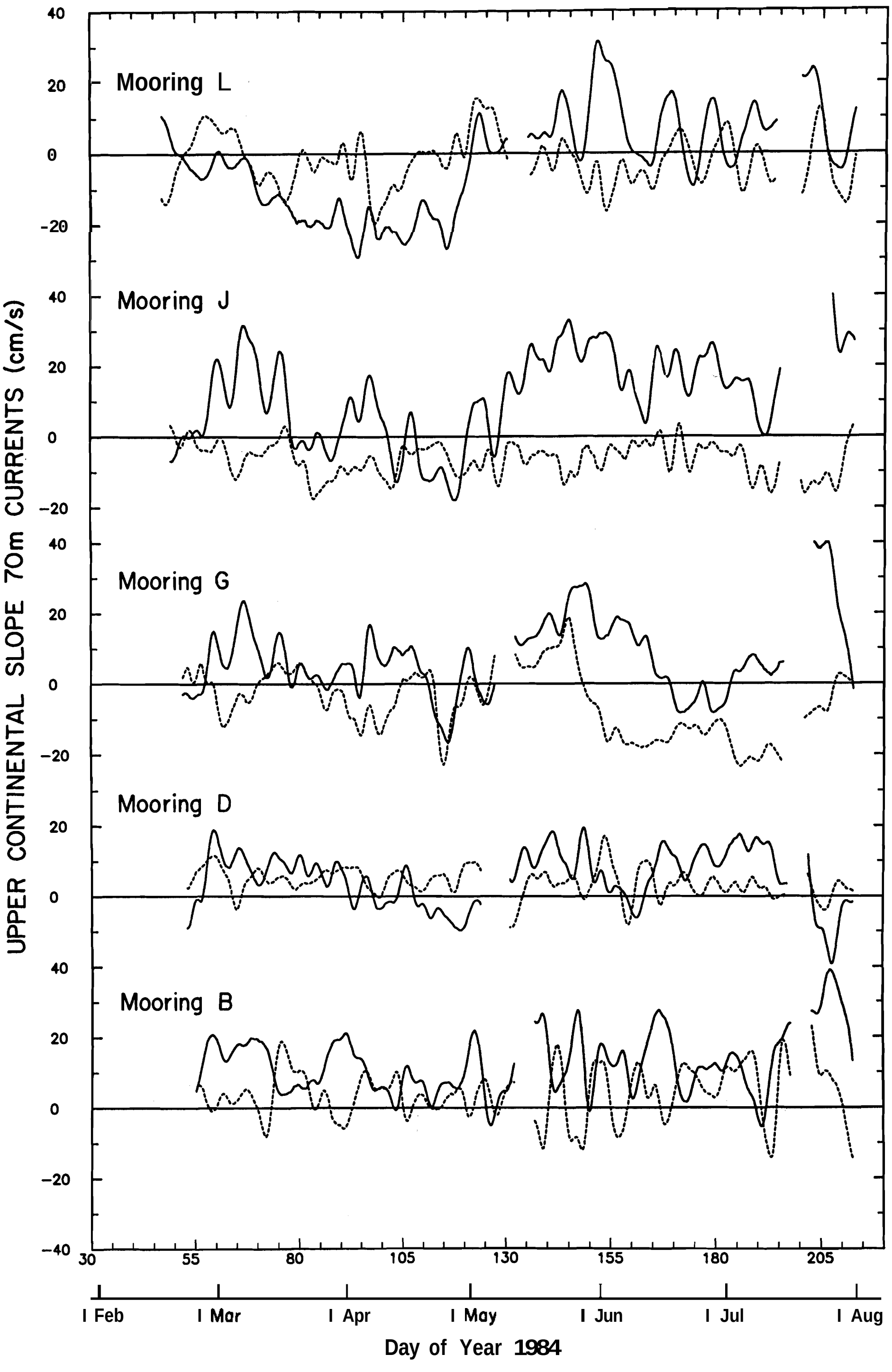

Fig. 6. Alongshore (solid lines, positive poleward) and cross-shore (dashed lines, positive onshore) currents at 70 m over the upper continental slope at CCCCS moorings B, D, G, J, and L for the period February–July 1984. Alongshore and cross-shore directions at each site were defined by the principal axes determined from the 6 months of data (Table 3).

During June and July, SST generally fluctuated in response to variable winds. The 70-m temperature was less correlated with winds. In mid-June, subsequent to the extended period of weak winds, SST increased by about 3°C and remained high through July. This warming was only weakly apparent at 70-m depth.

The alongshore component of 70-m currents at Super-CODE mooring P3 is shown in Figure 8*b* for the period February through July *1981.* There were several periods of weak equatorward flow over the first *4* months and one 2-week period of substantial equatorward flow in late March and early April. In general, however, the flow was poleward over the 6-month period, with typical speeds of 10 cm/s (comparable to that observed in *1984).* Consistent with the *1984* data, many of the pulses of strong poleward flow were associated with decreases or reversals of equatorward winds. The

TABLE 3. Maximum Correlations and Corresponding Time Lags Between 70-m Alongshore Currents at CCCCS Moorings and Alongshore Wind Stress

Mooring Site	Major Axis, °T	Wind Buoy	Maximum Correlation	95% Significance Level	Variance Explained, %	Lag of Maximum Correlation, days
				Shelf Moorings		
K	326.8	46012	0.73	0.34	53	0.25
F	304.1	46011	0.61	0.25	37	0.50
C	320.3	46011	0.61	0.26	37	0.00
A	302.0	46011	...	0.21	...	...
				Slope Moorings		
L	352.1	46012	0.40	0.34	16	1.25
J	316.1	46028	0.32	0.31	10	1.00
G	328.0	46011	0.36	0.31	13	0.75
D	334.7	46011	0.43	0.21	19	0.25
B	284.9	46011	...	0.23	...	...

Alongshore is defined by the major principal axes determined from the February–July 1984 time series as given in the table (see Table 1 for wind stress major principal axes). Also given in the table are the 95% significance levels of the correlations (computed as by *Chelton* [1983]), the percent variance explained by the correlations, and the lags of maximum correlation. Positive lags indicate that currents lag wind stress. Dots indicate that the correlation was not statistically significant at the 95% confidence level at any lags.

maximum correlation between alongshore wind stress and currents over the period February through July 1981 is 0.42, with winds leading currents by 0.25 day. This correlation value is lower than the value obtained at site C for the 1984 data but is still statistically significant (the 95% significance level is 0.23), indicating that local wind forcing of shelf currents was important during 1981 as well.

3. CalCOFI Hydrographic Measurements

The large-scale circulation in the California Current has been routinely surveyed since 1949 by CalCOFI. These hydrographic surveys cover the region from San Francisco to southern Baja California, extending offshore about 500 km. The relatively coarse 74-km grid spacing of the CalCOFI hydrographic measurements is well suited to studies of large-scale, low-frequency variability. From 1949 to 1969, CalCOFI surveys were conducted four or more times each year. Since 1969, the CalCOFI hydrographic surveys have been conducted at approximately monthly intervals every third year. The two most recent CalCOFI survey years for which data are presently available are 1981 and 1984, the same years for which shelf current measurements are available from SuperCODE and CCCCS as discussed in the preceding section.

Maps of surface dynamic height relative to 500 m depth are shown for July 1981 and 1984 in Figure 9. Relative geostrophic current speeds can be inferred from the spacing of dynamic height contours using the scales in the upper right corner of the figures. The July 1981 and 1984 maps show considerable similarity well offshore. In both years the core of the meandering equatorward California Current was located about 200 km offshore in the northern region and about 100 km offshore at about 35°N, with equatorward flow approximately 50% stronger in 1984 than in 1981. Closer inshore, the CalCOFI data indicate poleward surface flow along the entire central California coast in 1984. Poleward surface flow is evident as far north as Point Buchon in the 1981 CalCOFI data; farther north, the flow was very weak (essentially zero) within 100 km of the coast. (Note, however, that the 10-m salinity distribution in Figure 11 discussed below suggests poleward penetration as far north as Point Sur during 1981.)

This poleward or weak surface flow within 100 km of the coast observed in July 1984 and 1981 is unusual, based on the historical CalCOFI record. Normally, the surface flow in July is equatorward across the entire regime (Figure 1). The large-scale flow patterns during July 1984 and, to a lesser extent, July 1981 are more representative of the usual January pattern associated with the nearshore Davidson Current.

A feeling for the magnitude of the anomalous conditions during July 1984 and 1981 can be gained from the temperature-salinity (T-S) plots in Figure 10. The dots correspond to temperature and salinity values from all the historical July CalCOFI data through 1978, and the dashed line represents the seasonal average for July. Note that the spread of T-S values is larger at CalCOFI station 70.60 off Point Sur than at station 80.60 off Point Conception. In water deeper

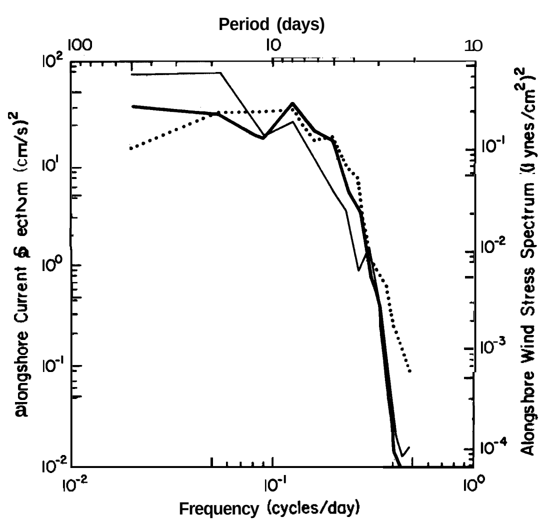

Fig. 7. Variance-preserving spectra of alongshore currents at shelf mooring F (heavy solid line) and upper slope mooring G (thin solid line), and alongshore wind stress at buoy 46028 (dotted line).

TABLE 4. Maximum Cross Correlations Between Alongshore Components of **70-m** Shelf Currents at the Four CCCCS Shelf Moorings and Between **70-m** Slope and Shelf Currents at Four Neighboring Pairs of CCCCS Slope and Shelf Moorings

Mooring Pair	Mooring Separation, km	Maximum Correlation	95% Significance Level	Variance Explained, %	Lag of Maximum Correlation, days
		Shelf Versus Shelf Currents			
K, F	221.1	0.57	0.33	33	0.5
K, C	296.0	0.31	0.30	10	1.5
K, A	369.6	···	0.22	···	···
F, C	75.2	0.61	0.22	37	0.25
F, A	148.5	···	0.30	···	···
C, A	74.8	0.32	0.27	10	1.5
		Slope Versus Shelf Currents			
B, A	14.3	0.33	0.19	11	−1.75
D, C	10.5	0.43	0.34	19	0.25
G, F	10.5	0.57	0.18	33	0
L, K	26.2	0.47	0.29	22	1.25

Alongshore is defined by the major principal axes (see Tables 1 and 3). Also given in the table are the mooring separations, the 95% significance levels of the cross correlations (computed as by Chelton [1983]), the percent of variance explained by the correlations, and the lags of maximum correlation. Positive lags indicate that currents at the first mooring lag currents at the second mooring. Dots indicate that the correlation was not statistically significant at the 95% confidence level at any lags.

than about 150 m, the July 1984 and 1981 *T-S* characteristics differ only slightly from the seasonal norm. However, at shallower depths, the July 1984 and 1981 *T-S* characteristics deviate dramatically from the seasonal norm. (Note the intrusion of near-normal *T-S* water centered at about 50-m depth, about 30 m shallower than normal, at station 80.60 during July 1981.) The *T-S* values in the upper 30 m at station 70.60 during July of both years were the most extreme in the CalCOFI record. Temperature values were near normal in the upper water column, but salinity values differed from normal by as much as 0.4%.

These higher salinities observed during July of 1984 and 1981 are representative of a water mass normally found farther south. The poleward penetration of this southern water mass is clearly evident in the maps of 10-m salinity in Figure 11. The anomalous water mass was characterized by nearly uniform salinity of 33.6% in both years. In the July seasonal average, water with 33.6% salinity is restricted to the extreme southeastern region from Point Conception to Point Buchon. In July 1981, water with 33.6% salinity was present as a tongue about 100 km wide extending as far north as about 36°N, where it was deflected offshore about 250 km. Similarly, in July 1984, water with 33.6% appeared as a tongue also about 100 km wide extending as far north as about 37°N, deflected offshore at Point Sur. In both years the poleward penetration and offshore deflection of this high-salinity water pushed the normal nearshore isohalines well offshore. Salinities in the far offshore region were near normal (within about 0.1‰). The result in both July 1984 and 1981 was a sharp meandering salinity front located about 100–200 km offshore.

The depth of penetration of the anomalous 33.6% salinity water in both years is evident from the vertical sections of salinity in Figure 12. During July 1981 the homogeneous pool of water extended to only about 50-m depth. In July 1984 the high-salinity water extended as deep as 75–100 m. The source of this high-salinity water could be either poleward advection from lower latitudes or upwelling. The flattening or slight downward tilting of isohalines very near the coast (superimposed on the larger-scale upward tilt across the full California Current) suggests that poleward advection is the dominant mechanism. This is further supported by the fact that the tem-

TABLE 5. Multivariate Regression of the Alongshore Component of **70-m** Currents v on Local Alongshore Wind Stress τ_y and Alongshore **70-m** Currents v_s at the Neighboring CCCCS Shelf Mooring to the South

Mooring Site	South Mooring Site	Wind Buoy	Maximum Correlation	95% Significance Level	Variance Explained, %	Lag of Maximum Correlation, days	Mooring Separation, km	Phase Speed, cm/s
K	F	46012	0.78	0.39	61	1.25	221.1	204.7
F	C	46011	0.73	0.26	53	0.50	75.2	174.1
C	A	46011	0.64	0.30	41	1.25	74.8	69.3

Alongshore is defined by the major principal axes (see Tables 1 and 3). The form of the regression is $v(t) = a\tau_y(t-t_1) + bv_s(t-t_2)$, where a and b are the regression coefficients. The lag t_1 for local wind forcing was fixed at 0.25 days, and the lag t_2 for currents to the south was varied from −1 week to +1 week. The maximum multiple correlations, 95% significance levels of the multiple carrelations (computed as by Chelton [1983]), and percent variance explained by the correlations are given in the table. Also listed in the table are the lag t_2 of maximum correlation, mooring separation, and the corresponding alongshore propagation phase speed (positive poleward).

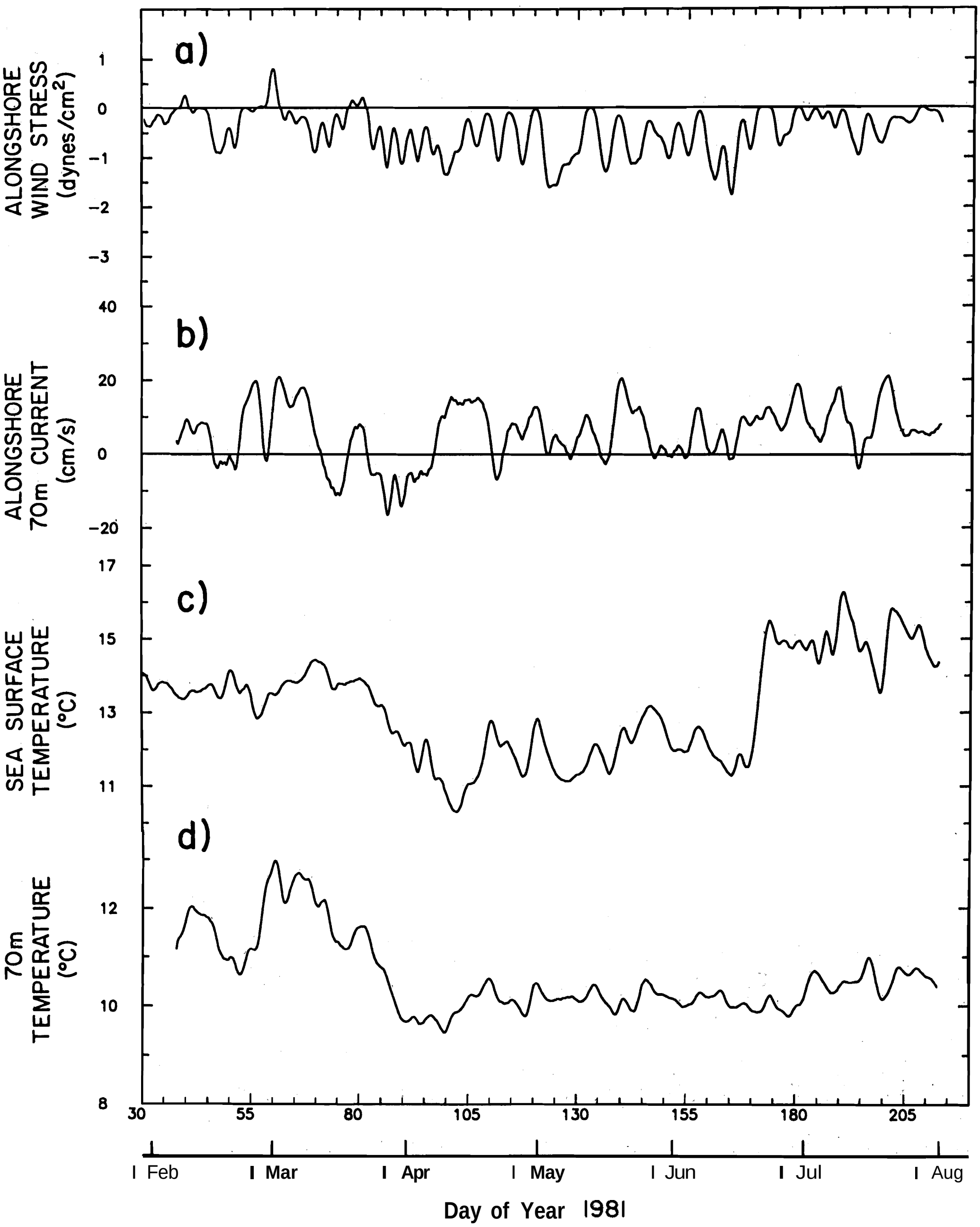

Fig. 8. Time series measurements for the period February through July 1981 of (a) alongshore wind stress at buoy 46011, (b) alongshore currents at 70 m at SuperCODE location P3, (c) sea surface temperature at buoy 46011, and (d) 70-m temperature at location P3. The alongshore direction for winds and currents is defined to be the principal axes determined from the 6 months of data, with positive values poleward (323.2°T for wind stress and 355.9°T for currents).

peratures associated with the high-salinity water in the T-S plots of Figure 10 are higher than the values that would be expected for upwelled high-salinity water.

The salinity distributions in Figures 11 and 12 are consistent with the picture of widespread poleward near-surface flow deduced from the dynamic height data (Figure 9). The July 1981 salinity map is suggestive of more extensive poleward flow than indicated by the dynamic height map. This salinity distribution may have resulted from strong poleward flow during June, prior to the July 1981 CalCOFI survey. There were no CalCOFI surveys during June 1981 to verify this.

As noted previously from Figures 4 and 8, there were extended periods of weak equatorward winds in late June and July of both 1981 and 1984. The relationship between winds during these 2 years and normal winds off central California is most easily examined from monthly Averages which effectively filter out the short time scale weather variability (Figure 13). In the seasonal cycle, monthly average alongshore wind stress increases steadily from February through May, remains constant during May and June, and then decreases by about 20% in July and August. During 1984 the magnitude of the alongshore wind stress was slightly higher than normal from February through April but dropped precipitously from May through July. During 1981 the alongshore wind stress was somewhat weaker than normal but followed the normal increasing trend from February through May. During June and July 1981 the alongshore winds decreased in magnitude to the same low values as were observed in 1984. The July monthly average for both years was less than 40% of the normal July average. The highly anomalous monthly average winds during June and July of 1981 and 1984 are almost certainly related to the widespread anomalous poleward flow observed over the continental slope from the July CalCOFI hydrographic surveys. In August of both years, the magnitude of the alongshore component of wind stress increased again but was still well below normal.

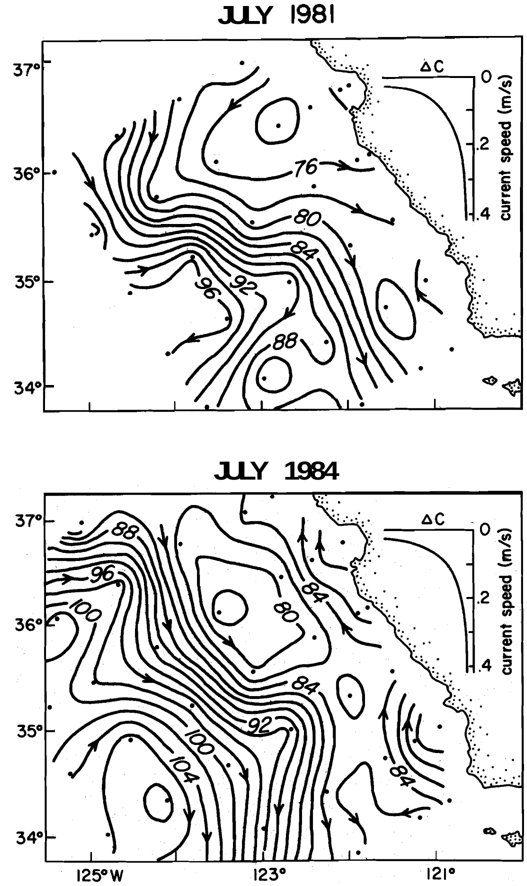

Fig. 9. Dynamic heights of the sea surface relative to 500 dbar determined from CalCOFI hydrographic data for July 1981 and July 1984. Arrows indicate the direction of relative geostrophic flow, and the scale in the upper right corner of each plot indicates the current speed for a given contour separation AC. The data shown in the figures were collected between June 28 and July 5, 1981, and between July 17 and 29, 1984.

4. CCCCS Hydrographic Data

As was noted previously, the CalCOFI hydrographic sampling grid is well suited to studies of large-scale variability. The station spacing is too coarse, however, to examine the detailed structure of variability over the continental shelf and upper continental slope. In 1984, higher horizontal resolution hydrographic measurements are available within 100 km of the coast from CCCCS hydrographic surveys made in February and July. The cross-shore station spacing of the CCCCS hydrographic data was 20 km, compared with the nominal 74-km CalCOFI station spacing. The inshore pattern of dynamic height and relative geostrophic flow inferred from the July survey (Figure 14) is consistent with that of the independent and lower resolution CalCOFI data: a somewhat meandering but continuous poleward flow from Point Conception to Point Sur. The CCCCS hydrographic data resolve structure in the geostrophic flow field that is not apparent in the coarsely sampled CalCOFI data. Note the indication from the CCCCS data of a jetlike feature extending offshore north of Point Sur between 36°N and 36.5°N. The velocity in this jet is not well resolved by the alongshore spacing of the CCCCS data, but strong offshore flow is clearly evident in the dynamic height field. Surprisingly, this feature is not evident in the CalCOFI data, apparently because of the coarser sampling grid.

The offshore jet north of Point Sur in July 1984 is consistent with the convergence of alongshore currents on the shelf discussed in section 2. From the current time series in Figure 5, convergence of shelf currents near Point Sur was a general feature for much of the period February through July 1984. One then expects offshore flow in this region to also be a general feature. In fact, relatively strong offshore flow was evident in the dynamic height field computed from the CCCCS survey conducted in February 1984 [see *Chelton et al.*, 1987, Figure 4]. Evidence for offshore flow near Point Sur is also present in many of the satellite images during the first half of 1984.

Kosro and Huyer [1986] present a detailed study of an offshore jet off northern California during CODE. They found that the offshore flow marked the boundary between two water masses. The offshore flow near Point Sur in Figure 14 also separates two very different water masses. The 10-m temperature and salinity fields from the July 1984 CCCCS data are shown in Figure 14. From the coarse alongshore station spacing of the hydrographic data, there are no distinctive features in the temperature field associated with the jet. However, the salinity field shows a strong front at the location of the jet. *T-S* plots for two CCCCS stations on opposite sides of the jet are shown in Figure 15. In water deeper than about 100 m, the *T-S* characteristics are similar at these two stations. The very different *T-S* characteristics in water shallower than about 30 m indicates that the offshore jet separates two distinctly different water masses. By comparison with the normal July *T-S* characteristics in this region, as shown by the dashed line in Figure 15, the mid-depth water mass (30–200 m) was anomalous at both of these CCCCS stations. However, the July 1984 *T-S* characteristics near the surface at station 67.60 were near normal for the region, indicating that north of the offshore jet the anomalous southern water mass was overridden by shallow equatorward flow of the normal northern water mass.

The cross-jet width of the salinity front is not well resolved by the alongshore spacing of the CCCCS hydrographic stations. Examination of the shipboard underway thermosalinograph data reveals that a 0.5‰ change in salinity across the jet occurred over a distance of less than 5 km in the

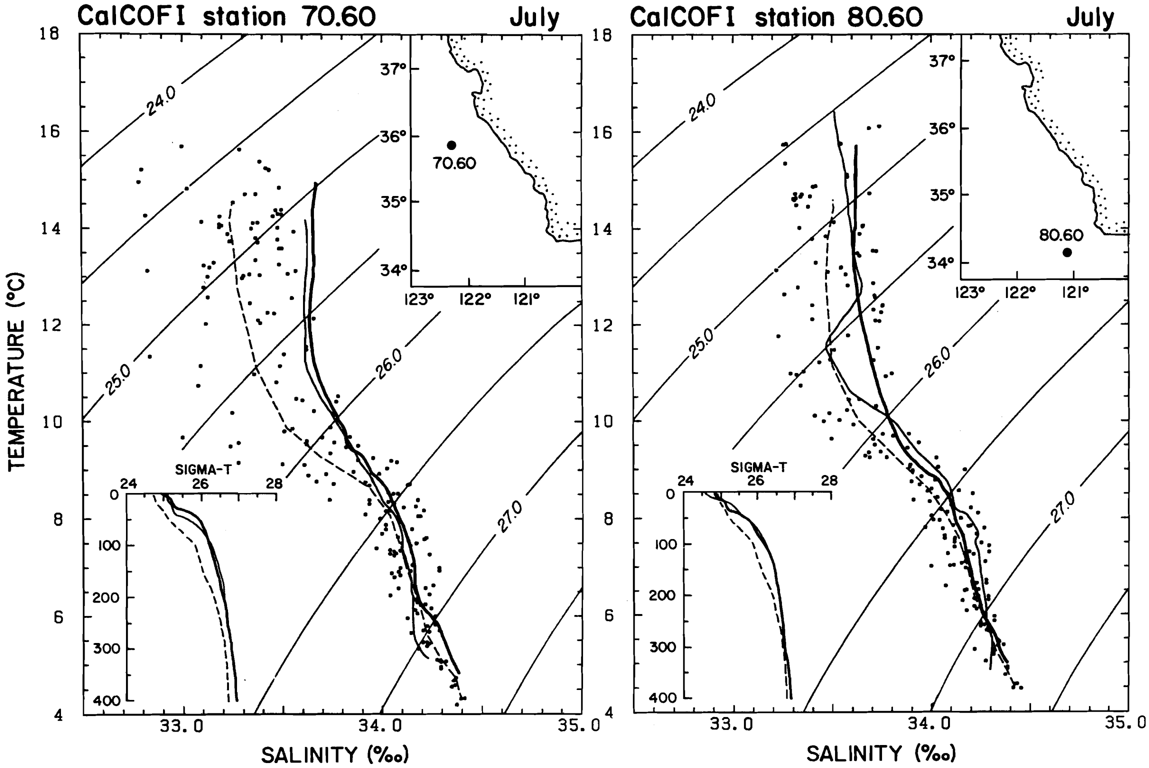

Fig. 10. Temperature-salinity (T-S) plots from CalCOFI hydrographic measurements at stations 70.60 and 80.60 over the upper continental slope (see map insets for station locations). The dots correspond to T-S pairs at 16 standard depths from the sea surface to 1000 m for all CalCOFI July measurements between 1950 and 1978. The dashed line through the center of the cluster of dots represents the July seasonal average at the 16 standard depths. The thin and heavy solid lines are the T-S plots from CalCOFI measurements in July 1981 and 1984, respectively. Depths of T-S pairs can be determined from the σ_t contours overlaid on the plot and the σ_t profiles in the lower left corner of the figure.

alongshore direction (Figure 16). With the 74-km alongshore spacing of the CCCCS hydrographic grid, the geostrophic velocities inferred from the dynamic topography thus significantly underestimate (by as much as a factor of 10) the velocity in the core of the jet.

The 20 km cross-shore spacing of the CCCCS hydrographic data allow an examination of the depth of penetration of the poleward flow during July 1984. Vertical sections of alongshore geostrophic velocity relative to 500 m are shown in Figure 17 for the six hydrographic lines in Figure 2. Lines 63 and 67 are poleward of the offshore jet discussed extensively above. Along these two northern lines, the near-surface flow was equatorward nearshore, with poleward flow present farther offshore. This pattern is consistent with the eddylike feature evident in Figure 14 centered 50 km offshore at about 36.5°N. At depths below 50–100 m, the flow was poleward along both lines. This is consistent with the 70-m currents at station K (on line 63), which were equatorward on average but poleward during July 1984 (see Figure 5). Along all four southern sections (lines 70, 73, 77, and 80), the alongshore velocity relative to 500 m was essentially poleward across the entire CCCCS sample domain (with the exception of a few patches of weak equatorward flow). This poleward relative velocity was most concentrated near the surface and nearshore; most of the flow was restricted to within 50 km of the coast. The highest relative velocities were 30–40 cm/s along each of the southern four sections.

5. SATELLITE IMAGERY AND DRIFTER MEASUREMENTS

Satellite SST data were collected for both 1984 and 1981. Such data can be very useful for characterizing surface flow conditions. The SST image data have been produced by a linear weighted sum of the 1-km-resolution 11- and 12-μm infrared brightness temperature measurements from the advanced very high resolution radiometer (AVHRR) carried on the NOAA 7 weather satellite. The weights used [*McClain et al.*, 19851 remove atmospheric water vapor absorption effects to yield SST estimates with absolute accuracy that may be as good as 1.O°C. Estimates of horizontal gradients of SST are much more accurate, since the spatial scale of atmospheric water vapor variability is large in relation to that of SST.

Selected satellite images for July of each year (Figure 18) show the SST distributions at approximately the same times as the CalCOFI hydrographic surveys shown in Figure 9. In both images, cooler water associated with coastal upwelling from the equatorward winds is evident immediately adjacent to the coast. Broad tongues of warmer water, with axes centered 50–100 km offshore, extend poleward from the southeastern corner of each image. Just to the west of the warm tongues is another region of cooler water associated with equatorward flow in the offshore region. These offshore meandering bands of cooler water coincide with the core of the equatorward California Current, as deduced from the CalCOFI dynamic height data (Figure 9).

Examination of these images, and others separated in time by a day or two, indicates that the flow in the warm water tongues in both *1984* and *1981* was drawing small nearshore filaments of cooler coastal water northward, clearly indicating **poleward** flow consistent with other evidence presented above.

Between July 6 and *15, 1984,* a total of *18* surface drifting buoys were released in three separate deployments into the warm water tongue north of Point Conception and then tracked by aircraft two to three times daily for about *2* weeks (Figure *19).* These CCCCS drifter tracks were generally somewhat erratic in the region immediately north of Point Conception, but the drifters moved rapidly **poleward** once north of Purisima Point. Thirteen of the drifters remained within the warm tongue, moving **poleward** along the coast at typical speeds of *10-20* **cm/s**; six of these drifters attained peak **poleward** speeds of over *50* **cm/s** between Point Buchon and Point Sur.

6. DISCUSSION

The large-scale seasonal variability of the California Current beyond the continental shelf break off central and southern California is well characterized by hydrographic measurements from the 35-year CalCOFI survey *[Hickey, 1979; Chelton, 1984; Lynn and Simpson, 19871.* The space and time scales of variability are characteristically shorter over the continental shelf than beyond the shelf break. Consequently, these shallow waters are not as well suited to studies purely from hydrographic data. Since few long-term current meter moorings have been deployed off the central California coast, seasonal variability over the shelf is not well known. Currents were measured at *11* locations off central California for the period February *1984* through July *1985* as part of the Central California Coastal Circulation Study. Owing to equipment failures, the shallowest CCCCS current meter measurements were at a depth of *70* m. These *70* m currents have been treated as representative of near-surface flow in this paper, though it must be kept in mind that the actual structure of currents near the surface is still not well known off central California.

The analysis results presented here show strong **poleward** flow on the shelf along the central California coast between Point Conception and Point Sur throughout the period February through July *1984.* With the exception of a few relatively short periods of weak equatorward flow, currents measured on the shelf off Purisima Point were also **poleward** for the same period in *1981.* Similar nearshore **poleward** flow has been previously observed throughout the year off Point Sur during *1979* and *1980* by ***Wickham et al.*** **[**1987**]** and off **Purisima** Point during *1981* and *1982* by ***Strub et al.*** **[**1987*b*]. The descriptive picture emerging from all of these observational studies is that **poleward** flow at depths near *70* m on the shelf appears to be normal throughout the year off the central California coast between Point Conception and Point Sur. This mean flow is in opposition to the prevailing equatorward winds and thus cannot be directly attributed to local wind forcing. North of Point Sur the mean flow was equatorward.

Correlation analysis presented in section *2* indicates that much of the variability of alongshore currents (deviations from the mean flow) on the shelf everywhere north of Point Conception is related to **fluctuations** in local alongshore wind stress. The current variations respond to wind forcing within

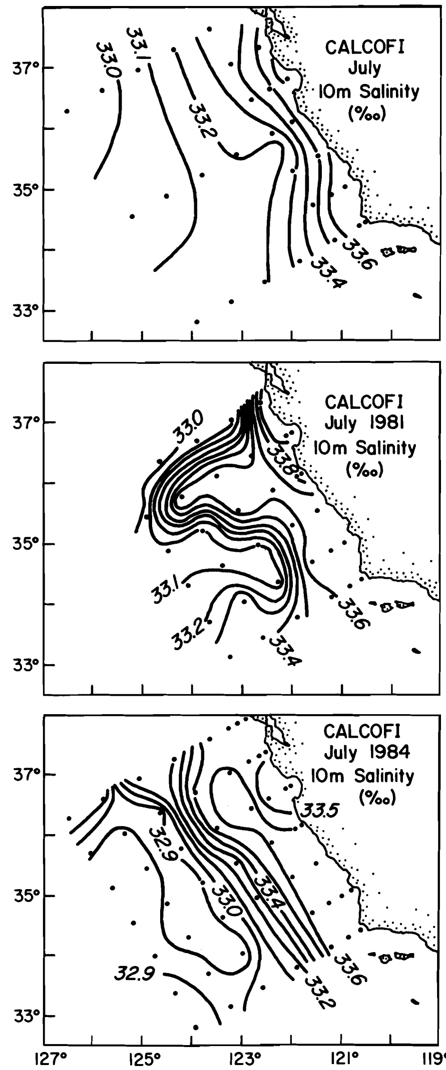

Fig. 11. Maps of salinity at 10-m depth from **CalCOFI** data for (top) the July seasonal average, (middle) July 1981, and (bottom) July 1984. The dates of the 1981 and 1984 measurements are given in the caption of Figure 9.

0.5 day, and evidence was presented for **poleward** propagation of shelf current variability north of Point Buchon at *175-200* **cm/s.** Although the percent variance in shelf currents additionally accounted for by **poleward** propagation was small, the phase speeds are consistent with those of the second-mode coastal-trapped wave estimated for the region by the model of ***Chapman*** **[**1987**]**. The observed phase speeds are approximately 30% slower than model estimates for the first mode coastal-trapped waves *[Battisti and Hickey, 1984; Denbo and Allen, 1987; Chapman, 19871.*

A similar coupling between shelf currents and local winds has been previously observed along the northern California coast as part of the Coastal Ocean Dynamics Experiment (CODE) **[*****Winant et al., 19871.*** Beyond the shelf break, the relation between current and wind variations is not as strong. The differences between shelf and slope currents are rather remarkable. Shelf and slope currents off central California separated by only **10–15** km cross shore are less well correlated

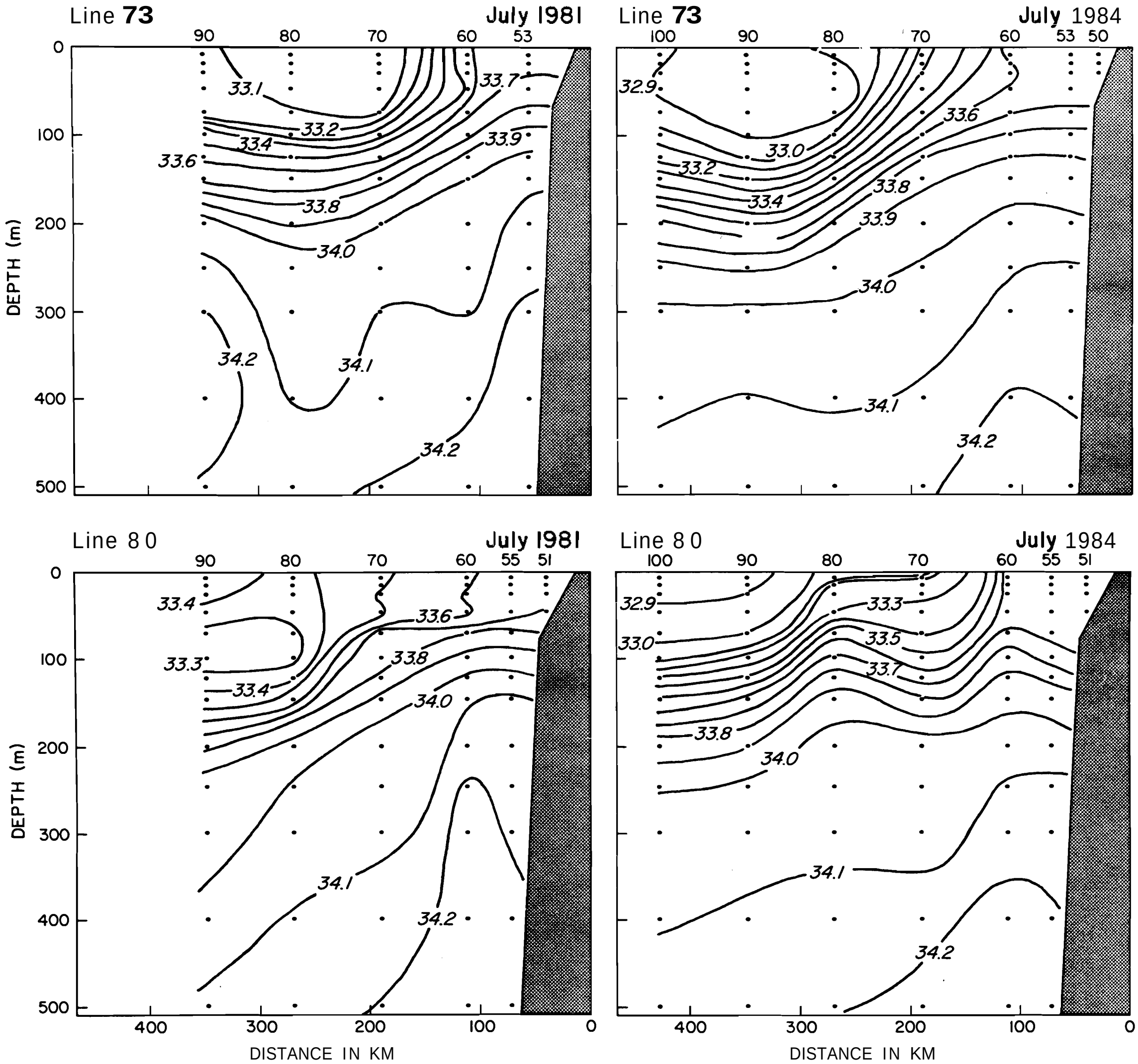

Fig. 12. Vertical sections of salinity from CalCOFI measurements along lines 73 and 80 during July 1981 and 1984.

than shelf currents separated by as much as 220 km alongshore. This is qualitatively consistent with the model results of *Brink et al.* [1987].

The differences in the direction of mean alongshore flow in the northern and southern portions of the sample region indicate a convergence of flow near Point Sur. Hydrographic surveys and satellite SST imagery show that this convergence is associated with strong offshore flow north of Point Sur. It was shown in section 4 that this offshore flow marked the boundary between two different water masses during July 1984. To the north of the offshore jet, the shallow waters were

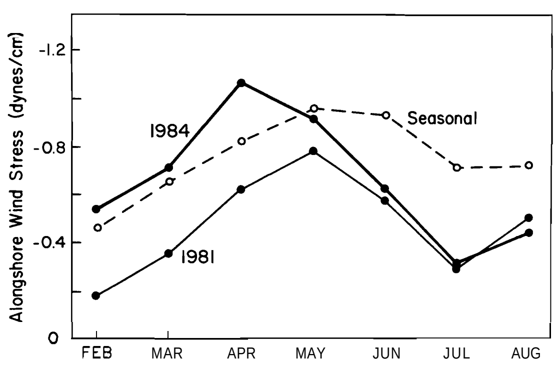

Fig. 13. Monthly average alongshore wind stress at buoy 46011 during 1984 (heavy solid line) and 1981 (thin solid line), and the seasonal average at 35°N (dashed line) determined from 100 years of ship observations [from *Nelson,* 19771. Note that the y axis is inverted.

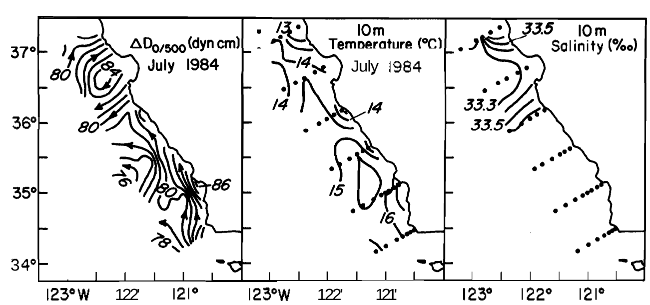

Fig. 14. Maps of (left) the dynamic height of the sea surface relative to 500 dbar, (middle) temperature at 10-m depth, and (right) salinity at 10-m depth from CCCCS CTD measurements during July 1984. Measurements were made between July 4 and 14, 1984.

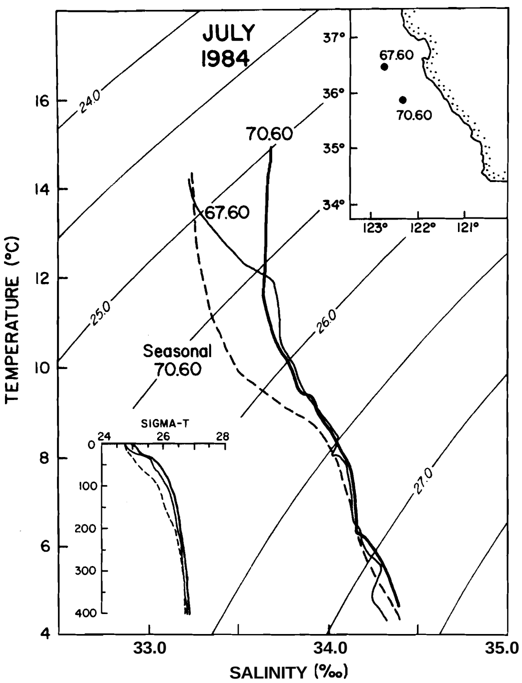

Fig. 15. *T-S* plots from July 1984 CCCCS CTD measurements at standard CalCOFI station locations 67.60 (thin solid line) and 70.60 (heavy solid line). Station locations are shown in the map inset. The dashed line corresponds to the July seasonal average at station 70.60 (from Figure 10). Depths of *T-S* pairs can be determined from the a, contours overlaid on the plot and the a, profiles in the lower left corner of the figure.

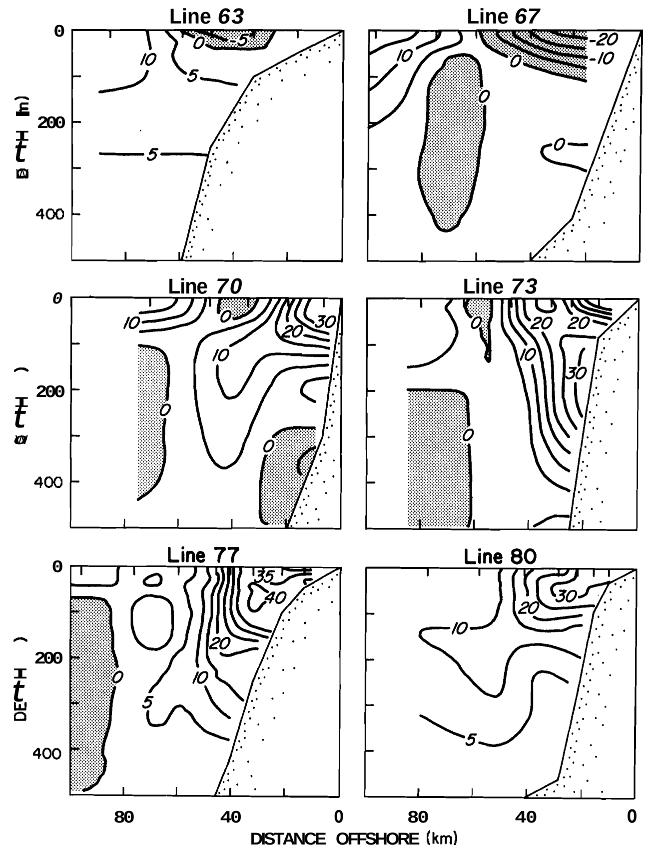

Fig. 17. Vertical sections of July 1984 alongshore geostrophic velocity relative to 500 dbar (contour interval is 5 cm/s) computed from CCCCS dynamic height measurements along the six standard CalCOFI lines shown in Figure 2. Tick marks along top of each plot indicate locations of CTD stations. Shaded regions indicate equatorward flow. Dynamic heights used to compute the relative velocities inshore of the 500-m isobath were extrapolated from deeper water using the method described by *Reid and Mantyla* [1976]. Measurements were made between July 4 and 14, 1984.

characterized by low salinities typical for the region during July. The water mass south of the jet was of lower-latitude origin with salinities higher by about 0.3‰.

results presented in this study suggest that anomalous weak winds along the central California coast in June and July of 1981 and 1984 may have been responsible for the intensification of poleward flow on the continental shelf and the appearance of more widespread poleward flow farther offshore over the continental slope. From the hydrographic data and satellite imagery presented here for 1981 and 1984, it appears that this poleward flow can spread as far as 100 km offshore following extended periods of weak equatorward winds. Such widespread poleward flow is normally associated with the wintertime Davidson Current but is highly unusual during summer. On the basis of historical temperature and salinity characteristics for the region, July 1984 and 1981 were the most extreme anomalous summertime conditions on record off the central California coast.

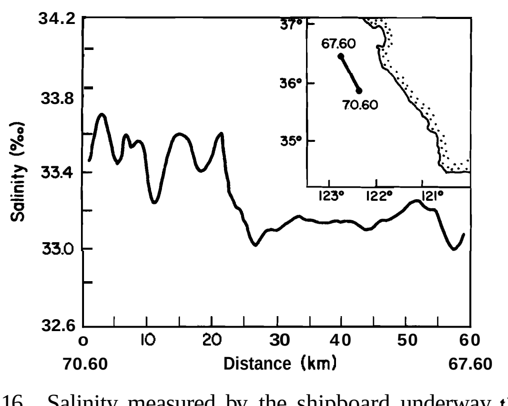

Fig. 16. Salinity measured by the shipboard underway thermosalinograph along the transect from station 70.60 to station 67.60 shown in the map inset. The locations of the two stations are labeled along the distance axis on the bottom.

Huyer and Kosro [1987] and *Send et al.* [1987] examined coastal current response to relaxation from upwelling off northern California during CODE. They observed a relaxation phenomenon having features in some respects comparable to those presented here, the most notable being the appearance of poleward surface flow and associated warm water when the equatorward upwelling-favorable winds subsided. The modeling results of *Send et al.* [1987] indicate that a large percentage of the near-surface (upper 30 m) thermal variability very near the coast off northern California can be explained by variations in near-surface heat flux and by poleward advection of heat by surface currents.

The observations presented here contrast those of *Huyer and Kosro* [1987] and *Send et al.* [1987] in two important respects. The poleward flow observed during CODE was coastally trapped to a narrow region over the continental shelf and persisted for time scales of only about a week. In contrast, the poleward flow observed off central California extended

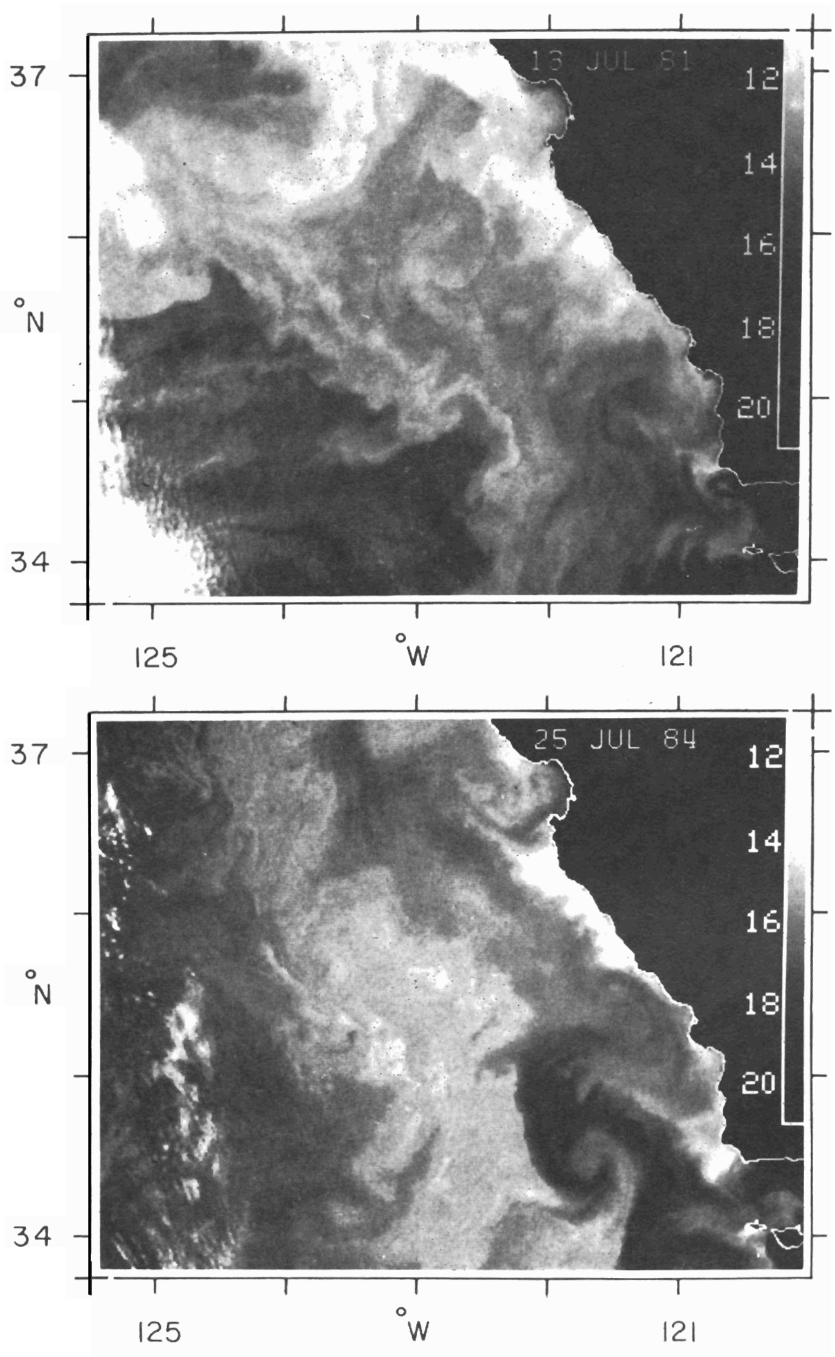

Fig. 18. AVHRR infrared sea surface temperature images for July 13, 1981, and July 25, 1984. The gray scale for sea surface temperatures is shown along the right side of each image.

well offshore beyond the shelf break (by as much as 100 km) and was present throughout most of the first 6 months of 1984 and 1981.

A final point worth noting is the unique character of current variability off Point Conception. Currents at shelf and slope moorings off Point Conception were unrelated to local wind forcing and uncorrelated with currents farther north along the central California coast. The independent nature of currents in this region is further confirmed from drifter trajectories and satellite SST imagery, both of which show high spatial variability in the surface flow just north of Point Conception. ***Chelton*** [1984] and ***Brink and Muench*** [1986] have previously shown that the flow at Point Conception is highly coupled to the circulation inside the Santa Barbara Channel. This is supported by the modeling results of ***Battisti and Hickey*** [1984] and ***Chapman*** [1987]. The flow into and out of the Santa Barbara Channel evidently does not in any simple way influence the circulation north of Point Conception. However, occasional pulses of strong westward flow through the Santa Barbara Channel may be responsible for the warm, saline water found adjacent to the coast of central California as far north as Monterey Bay in July 1981 and 1984.

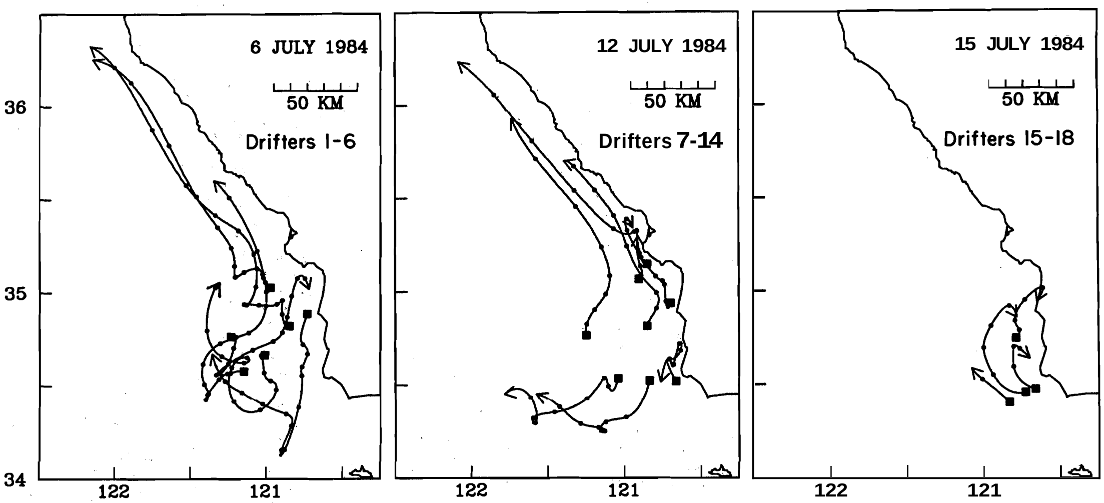

Fig. 19. Drifter trajectories for three CCCCS deployments during July 1984. Boxes indicate drifter release points and dots along trajectories are separated in time by 1 day.

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