POLEWARD FLOW IN THE CALIFORNIA CURRENT SYSTEM

Adriana Huyer
P. Michael Kosro
College of Oceanography
Oregon State University
Corvallis, OR 97331

Steven J. Lentz
Robert C. Beardsley
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

INTRODUCTION

In the California Current System, poleward flow has been observed at different levels and in different seasons. In winter, there is broad poleward flow at the surface along most of the coast along Washington, Oregon, and northern California. During the upwelling season, in spring and summer, there is a narrow, inshore poleward surface current which appears off northern California whenever upwelling-favorable winds weaken; off southern and central California, this inshore poleward flow seems to persist through most of the upwelling season. During the upwelling season, there is also subsurface poleward flow, both near the bottom over much of the continental shelf and at depths of a few hundred meters along the upper continental slope. Whether and how these "branches" of poleward flow are related to each other is still unknown. We have some ideas of how the surface poleward flows are driven, but still very little information on the continuity and the driving of the subsurface undercurrents. In this note, we shall summarize briefly the main characteristics of each of these "branches," and present some recent observations of the California Undercurrent in the CODE region near San Francisco.

POLEWARD FLOW AT THE SURFACE: THE DAVIDSON CURRENT

Broad Northward Flow in Winter

The first evidence of a northward surface current along the west coast of North America was the use of redwood logs by North Coast Indian tribes in making dugout canoes and totem poles. This inferred northward flow was called the Davidson Current in honor of Professor George Davidson who was one of the early surveyors of the west coast. Systematic observations of the surface currents at lightships between San Francisco and the Strait of Juan de Fuca (Marmer, 1926) showed predominantly northward flow from October through March at all locations, with the strongest monthly-mean northward flow (20-30 cm/sec) occurring in January or February each year. Drift bottle releases (Wyatt et al., 1972), near-surface drogues (Reid and Schwartzlose, 1962), repeated hydrographic sections (Huyer, 1977; Chelton, 1984), and current measurements over the midshelf and shelfbreak (Hickey, 1981; Strub et al., 1987) all indicate that this winter northward surface current is considerably wider than the continental shelf, at least at latitudes north of Point Conception. The strongest northward flow (with a typical monthly mean of 15 cm/sec at the surface) occurs over the inner shelf, adjacent to the coast (Huyer et al., 1978). There seems to be considerable year-to-year variability in the strength of this current; during the El Nino winter of 1982-1983, the northward current was twice as strong as in the preceding and subsequent "normal" years (Huyer and Smith, 1985).

This winter northward surface current seems to be forced by the winter southeasterly winds which cause downwelling of the surface waters at the coast. This downwelling, combined with the increased coastal runoff caused by winter rains, results in an offshore density gradient which is in approximate geostrophic balance with the vertical shear of the northward current (e.g., Huyer et al., 1979).

Inshore Northward Flow

Poleward surface currents have also been observed during the upwelling season, with particular frequency and persistence along the coast of southern and central California. These northward flows apparently occur inshore of the coastal upwelling jet which flows equatorward along the front between dense, freshly-upwelled coastal waters and lighter oceanic surface waters. In the Southern California Bight, this inshore northward flow prevails most of the year, disappearing for only a month or so each year in March or April (Tsuchiya, 1980). The inshore poleward flow here may be as wide as 100 km or more; it seems to form the inshore limb of a large cyclonic eddy that fills most of the Bight (Reid et al., 1958). Further north, in the CODE region near San Francisco, an inshore countercurrent appears whenever upwelling-favorable winds relax (Send et al., 1987) and disappears when they become unusually intense (Winant et al., 1987). This inshore countercurrent is only 10-20 km wide and can have velocities of > 30 cm/sec (Kosro, 1987); it seems to become more persistent as the upwelling season progresses (Winant et al., 1987). Off central Oregon, a similarly narrow, inshore countercurrent is frequently observed in mid- and late summer (Stevenson et al., 1974; Kundu and Allen, 1976).

These inshore countercurrents may be driven partly by along-shore pressure gradients which are set up to balance the strong equatorward wind stress: when the winds relax, the residual pressure gradient causes a northward acceleration. This mechanism has been invoked to explain the rapid reversals of flow over the Pacific Northwest shelf that occur whenever previously strong winds relax (Hickey, 1984). However, the details of the dynamics involved are not yet clearly understood: in particular, the along-shore scales of the relevant pressure gradients are unknown, and both the sign and magnitude of estimates of the pressure gradient are sensitive to the choice of scale. There may well be other processes and dynamics involved.

UNDERCURRENTS OVER THE SHELF

Moored current measurements over the continental shelf off Washington and central Oregon have consistently shown a poleward undercurrent along the bottom over the mid- and outer-shelf during the summer upwelling season (Mooers et al., 1976; Huyer et al., 1975a, b). This undercurrent has its maximum strength within 20-30 m of the bottom (Huyer et al., 1978). Maximum velocities are relatively weak: monthly means of 2-5 cm/sec are typical. Similar undercurrents have been observed over the shelf in the CODE region just north of Point Reyes (Winant et al., 1987; their Figure 19b), and off Half Moon Bay at 37.4°N and Purisima Point at 34.8°N (Strub et al., 1987; their Figure 7). This undercurrent is absent immediately after the spring transition which marks the onset of seasonal upwelling (Huyer et al., 1979; Lentz, 1987), but it appears within a few weeks and slowly intensifies through the summer. In fall, the depth of the current maximum seems to shoal (Reid, 1987), and the shelf undercurrent becomes indistinguishable from the northward surface current which extends across the entire shelf in late autumn and winter.

Why the maximum velocities are observed so near the bottom and how this shelf undercurrent is driven remain uncertain. It seems increasingly likely that what we are observing here is merely the upper and inshore portion of the larger undercurrent that flows poleward along the upper continental slope, which is often called the California Undercurrent.

POLEWARD FLOW ALONG THE CONTINENTAL SLOPE: THE CALIFORNIA UNDERCURRENT

A poleward undercurrent over and along the continental slope has been observed at several latitudes between Baja, California and Vancouver Island. Indirect evidence for this flow is clearly visible in the large-scale temperature-salinity characteristics of coastal waters as northward-tending tongues of relatively warm, saline water (Tibby, 1941; Reid et al., 1958). More detailed studies of particular regions (e.g., Wickham, 1975; Reed and Halpern, 1976; Freitag and Halpern, 1981) also show a concentration of waters of more southerly origins along the continental margin. The undercurrent can also be clearly seen in the dynamic topography (AD) of isobaric surfaces of 150–300 dbar (relative to a deeper isobaric surface): in the maps of $\Delta D_{200/500}$ from repeated CalCOFI surveys off Baja, California and southern California (Wyllie, 1966); in a map of ΔD 300/900 covering slope waters off northern California in May 1977 (Freitag and Halpern, 1981); and in maps of $\Delta D_{150/1000}$ off Washington and Oregon in September 1973 (Reed and Halpern, 1976) and July 1975 (Halpern et al., 1978). Freitag and Halpern (1981) estimate a northward transport of 1–3 Sv along the slope. Analysis of repeated CalCOFI sections shows that the undercurrent off Point Conception (Chelton, 1984; his Figure 3) persists year-round, has a width of 50–100 km, is strong (> 7 cm/sec) and shallow (core at 100 m) in winter, and weak (< 3 cm/sec) and deep (core at 250 m) in early spring; the lateral and vertical shears along the undercurrent are strongest from May through August. Similar analysis of sections off Point Sur (Chelton, 1984; his Figure 2) shows only a weak (3 cm/sec) undercurrent in late summer (July to September) that seems to shoal, intensify, and merge with the Davidson Current in winter, and to disappear in spring and early summer (March to June).

Direct measurements of this northward flow were first made by deploying parachute drogues and tracking them for several days. Reid (1962) found a 20 cm/sec northward current, about 75 km wide, at a depth of 250 m off Monterey (36°N) in November 1961. Wooster and Jones (1970) found a very narrow (20 km) undercurrent with a speed of about 30 cm/sec at about 31°N off Baja, California in August 1966. However, Stevenson et al. (1969) failed to find a northward undercurrent off Oregon in most of their 15 drogue deployments between January 1962 and September 1965.

Longer-term direct measurements of the northward flow required the installation of moored current meters. Prior to the CODE experiment conducted in 1981 and 1982, moorings of at least a few weeks duration were successfully deployed at several locations along the continental slope (Figure 1). The most complete sections, showing the most detailed vertical and offshore structure, were obtained off southern Washington in the

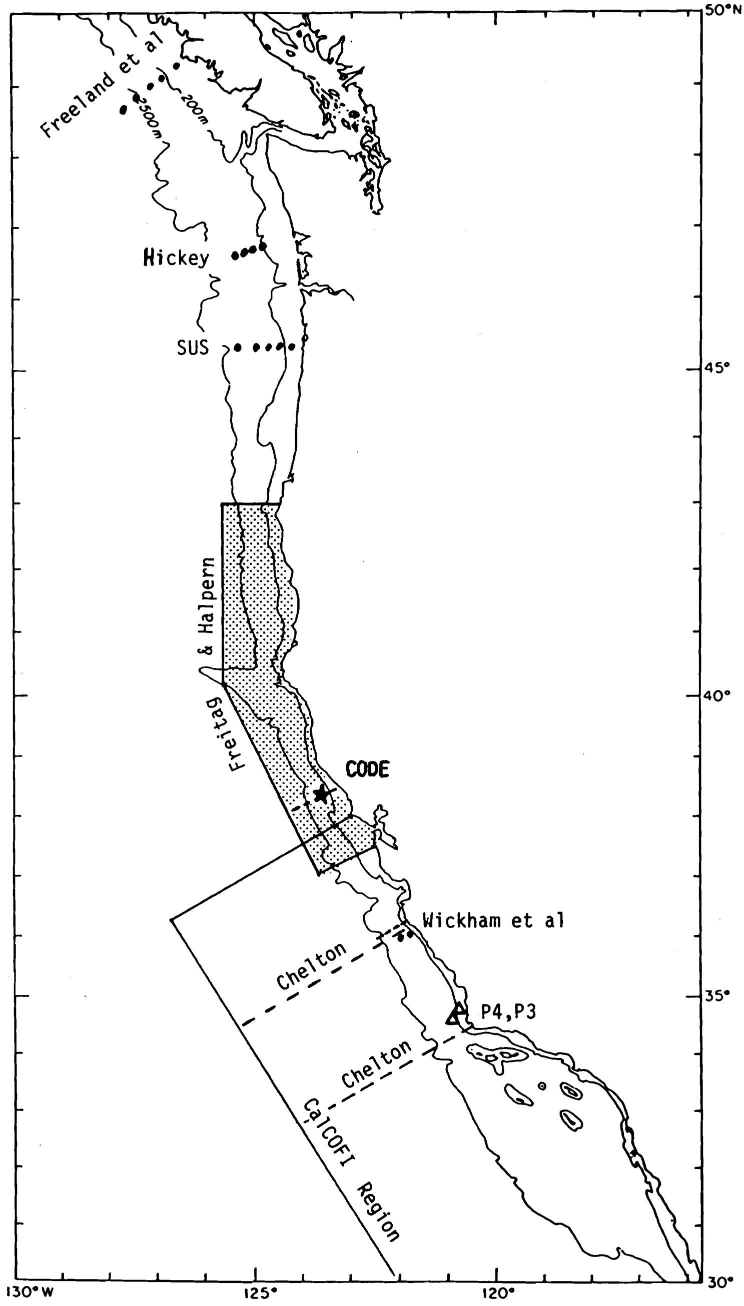

Figure 1: Map of a portion of the west coast of North America, showing the location of the principal historical studies of the poleward undercurrent along the continental slope. Repeated hydrographic sections are indicated by dashed lines, and moorings of at least a few weeks duration are indicated by dots. The **CODE** C-5 mooring is indicated by a star and the shelf moorings off Purisima are indicated by triangles.

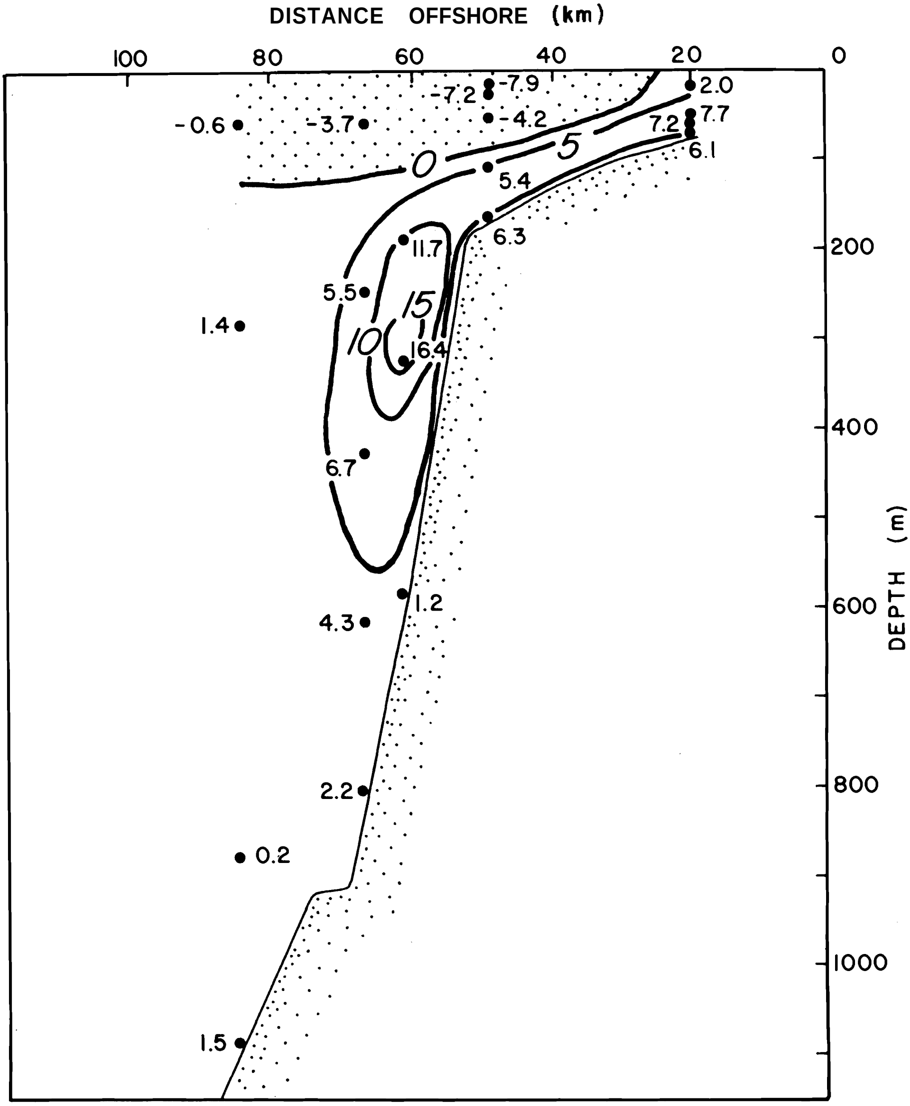

Figure 2: The distribution of the mean along-shore flow off southern Washington, 21 July to 28 August 1972. Adapted from Hickey (1979).

summer of 1972 (Hickey, 1979) and off Vancouver Island in the summer of July 1980 (Freeland et al., 1984). Average along-shore velocity sections from these arrays are shown in Figures 2 and 3; in both cases, the average was calculated over a period of about a month, in summer. Both show that the poleward velocity has a definite maximum adjacent to the continental slope, but the depth and strength of this core are rather different. Off Washington in 1972, the 15 cm/sec maximum occurs at a depth of about 300 m; off Vancouver Island in 1980, the 4 cm/sec maximum occurs at a depth

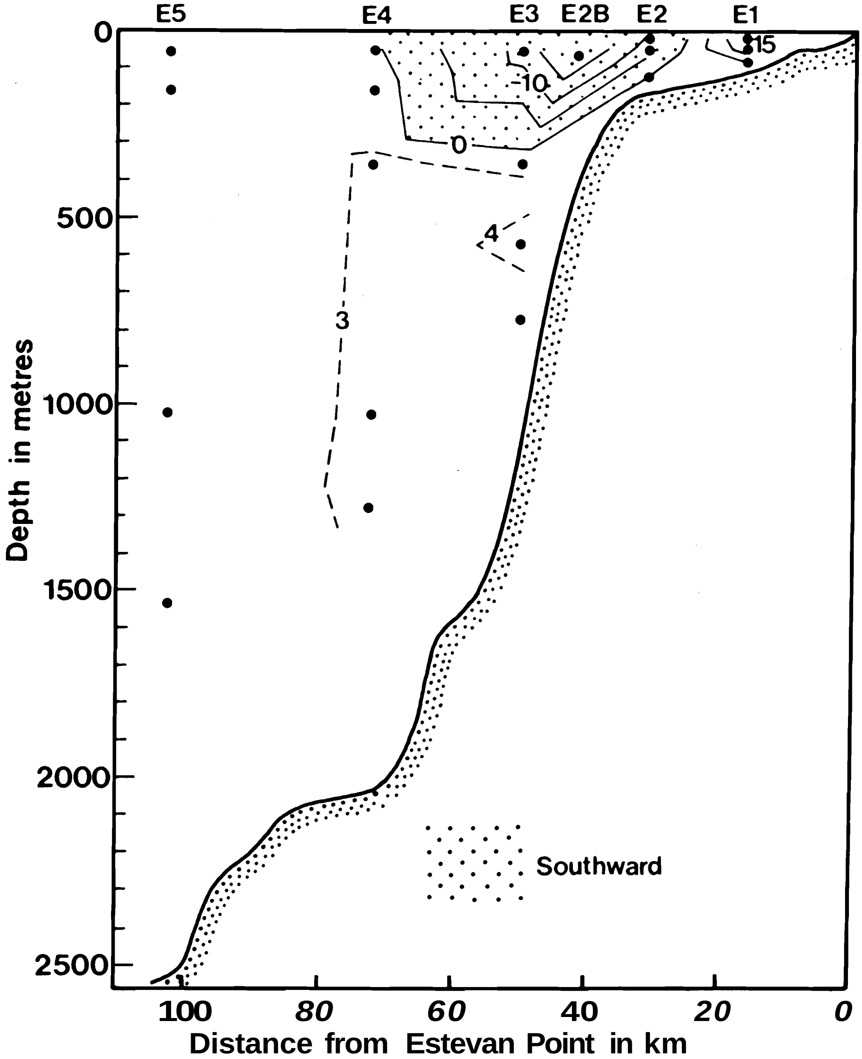

Figure 3: The distribution of the mean along-shore flow off Vancouver Island, July 1980. From Freeland et al. (1984).

of 600 m. We do not know whether these differences are associated with the difference in location or with the difference in years; i.e., whether they reflect spatial or interannual variations. The difference is probably not seasonal, since the data sets were taken at very nearly the same time of year.

A Slope Undercurrent Study (SUS) designed to observe the seasonal variation of the undercurrent off central Oregon in 1977 and 1978 met with limited success. An earlier mooring there had shown a definite undercurrent over the upper slope (500 m isobath), with the strongest northward current (5 cm/sec) near the bottom (Halpern et al., 1978). There were five moorings in this array, spanning the entire continental margin; unfortunately, there were more instrument failures and losses to fishing than usual, and a strong warm-core eddy remained over the offshore moorings for more than two months in January and February 1978 (Huyer et al., 1984). Nevertheless, the results do indicate some seasonal differences (Figure 4): in winter, there is broad northward flow (presumably the Davidson Current) over the entire margin; in spring, there is predominantly southward flow with a weak (5 cm/sec) undercurrent near the shelf-break; and in summer, there is still a weak undercurrent over the shelf-break and an apparently separate broad poleward flow over the outer margin. These sections look very different from those from the southern Washington and Vancouver Island sites (Figures 2 and 3). The data from the upper slope during summer 1978 is very similar to the summer 1975 data (Halpern et al., 1978) taken at a nearby location. We, therefore, think that much of the difference should be attributed to the shape of the continental margin, which is much wider here than farther north.

Current meter moorings were deployed for several two-month intervals at three sites over the upper slope near Point Sur between July 1978 and July 1980 (Wickham et al., 1987). Although there was little temporal overlap in the data from different moorings, the results indicate that the strongest poleward flow is adjacent to the upper slope. The strongest average flow (15 cm/sec) was obtained at the shallowest current meter, at a depth of about 100 m, only 10 km from shore; geostrophic velocity sections indicate there was southward flow at shallower depths. If these observations are assumed to be representative of the flow regime off Point Sur, we would infer that the undercurrent is much shallower there than off Oregon, Washington, and Vancouver Island. This shoaling of the undercurrent to the south is supported by the long-term shelf moorings deployed along the west coast in 1981 and 1982; the upper instruments from these moorings show an increasing tendency for northward flow at more southerly sites (Strub et al., 1987a). In particular, the moorings off Point Purisima at 34.8°N show persistently northward flow (Figure 5) which is interrupted for only a few weeks in early spring (in March 1981 and April 1982).

Data from the CODE *C-5* Mooring

During the Coastal Ocean Dynamics Experiment conducted over the continental shelf and slope between Point Arena and Point Reyes, a pair of current meter moorings were maintained at 38.5°N, 123.7°W over the 400 m isobath on the upper slope (Winant et al., 1987). One of the moorings

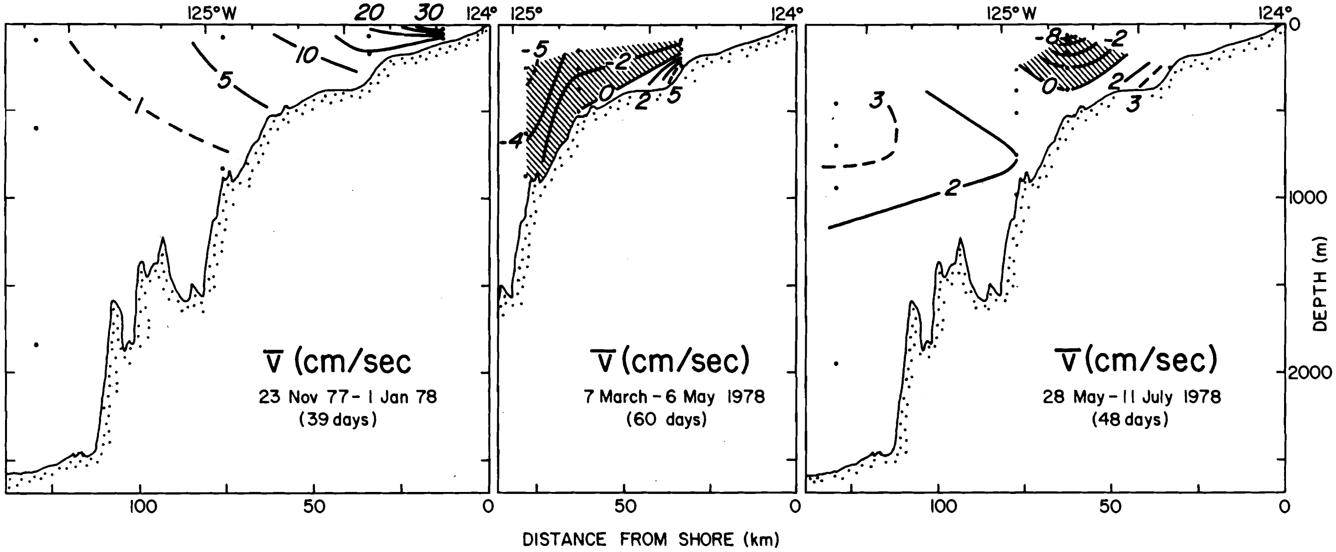

Figure 4: The distribution of average along-shore flow off central Oregon for three periods between November 1977 and July 1978. From Huyer et at. (1984).

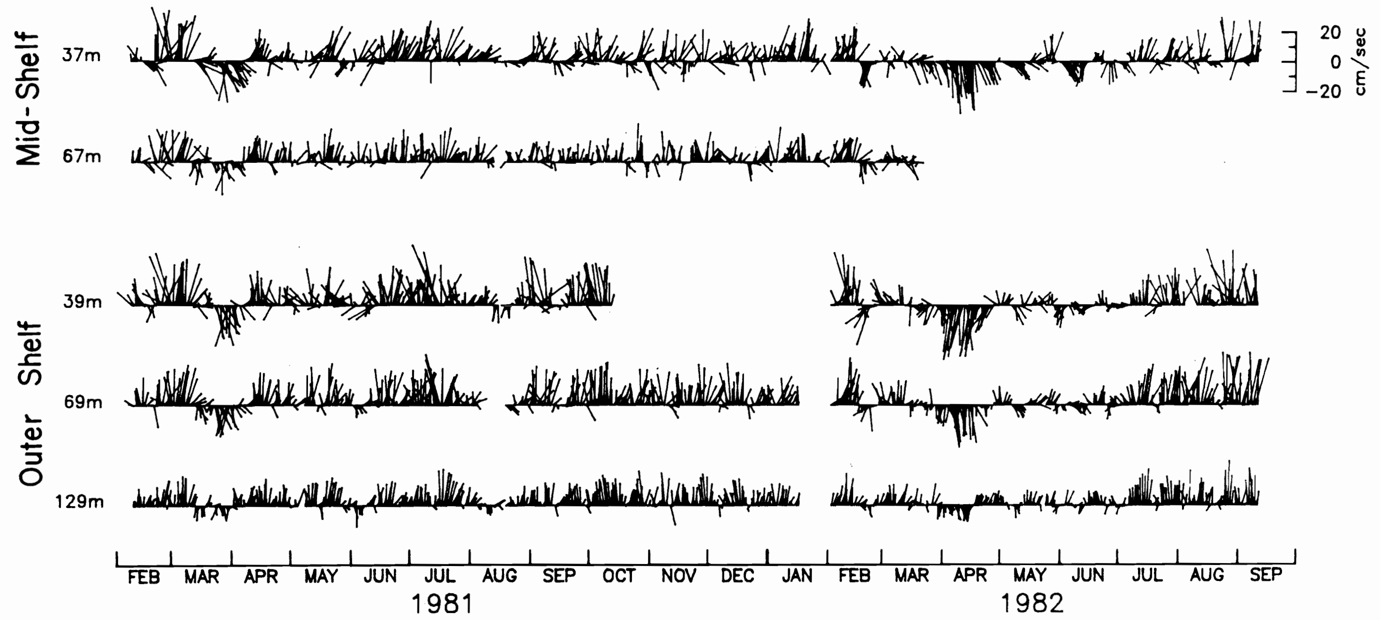

Figure 5: Time series of daily low-passed (<0.6 cpd) current vectors over the mid-shelf and outer-shelf (P3 and P4, over the 90 and 155 m isobath, respectively), off Purisima Point at 34.8°N, February 1981 to September 1982. Vectors are oriented so that true North is at the top of the page. Replotted from Denbo et al. (1984).

had surface flotation and a vector-averaging current meter (VACM) at 9 or 10 m; the other mooring was entirely subsurface, with instruments at or very near 75, 150, 250, and 350 m. The moorings were installed in April 1981, serviced in August, December, and April, and finally recovered in August 1982; these observations preceded the onset of El Nino conditions in October 1982 (Huyer and Smith, 1985). Current records at the same (or similar) depth from consecutive installations were joined by applying a predictive filter (Ulrych et al., 1973) to fill the short gaps in the hourly data. The 9 m record has a two-month gap due to an instrument failure in October 1981, but the records at the other depths are complete. The joined records were low-pass filtered (half-power at 0.6 cpd) to suppress tidal and inertial fluctuations; a coordinate rotation yielded onshore (toward 65°T) and along-shore (toward 355°T) components of the current. Time series of twelve-hourly low-passed current vectors (Figure 6) show considerable variability on time scales of days and weeks; nevertheless, it is clear that equatorward flow predominates at the surface and poleward flow predominates at depths greater than 100 m (Figure 6, Table 1). Both the equatorward surface current and the poleward undercurrent seem to be strongest in the season when the local wind stress (calculated from winds measured at nearby NDBC Buoy 13; Beardsley et al., 1987) is persistently favorable for upwelling. This is seen more clearly in the vertical profiles of three-month averages of the along-shore current (Figure 7, Table 2) which show that the undercurrent is strongest (averaging about 10 cm/sec) in spring and summer, and absent or very weak in winter. Since the spring profiles from the two years are very similar (both show strong mean vertical shear and an undercurrent core-depth of 250 m), it seems likely that they are representative for this location. However, we do not know how large a region the C-5 mooring site represents—it may be only a few kilometers across. Repeated current measurements by means of a shipborne doppler acoustic profiler along sections at 38.5°N and 39°N indicate that there are significant differences in the strength and structure of the under-current between lines separated by only 50 km (Huyer and Kosro, 1987; their Figure 27). Preliminary analysis of T-S characteristics along a section through C-5 suggests that the undercurrent core-depth is more than 100 m deeper over the mid-slope than at C-5, a separation of only a few kilometers; more work will need to be done to verify this result and to grasp its implications. On the other hand, preliminary results from recent moorings over the upper slope at other locations between Monterey and Point Conception (Chelton et al., 1987) seem to indicate vertical profiles that are similar to those observed at C-5; again, more work will be needed to verify this.

As yet, we still have a very incomplete picture of the California Undercurrent that flows poleward along the continental slope. We think

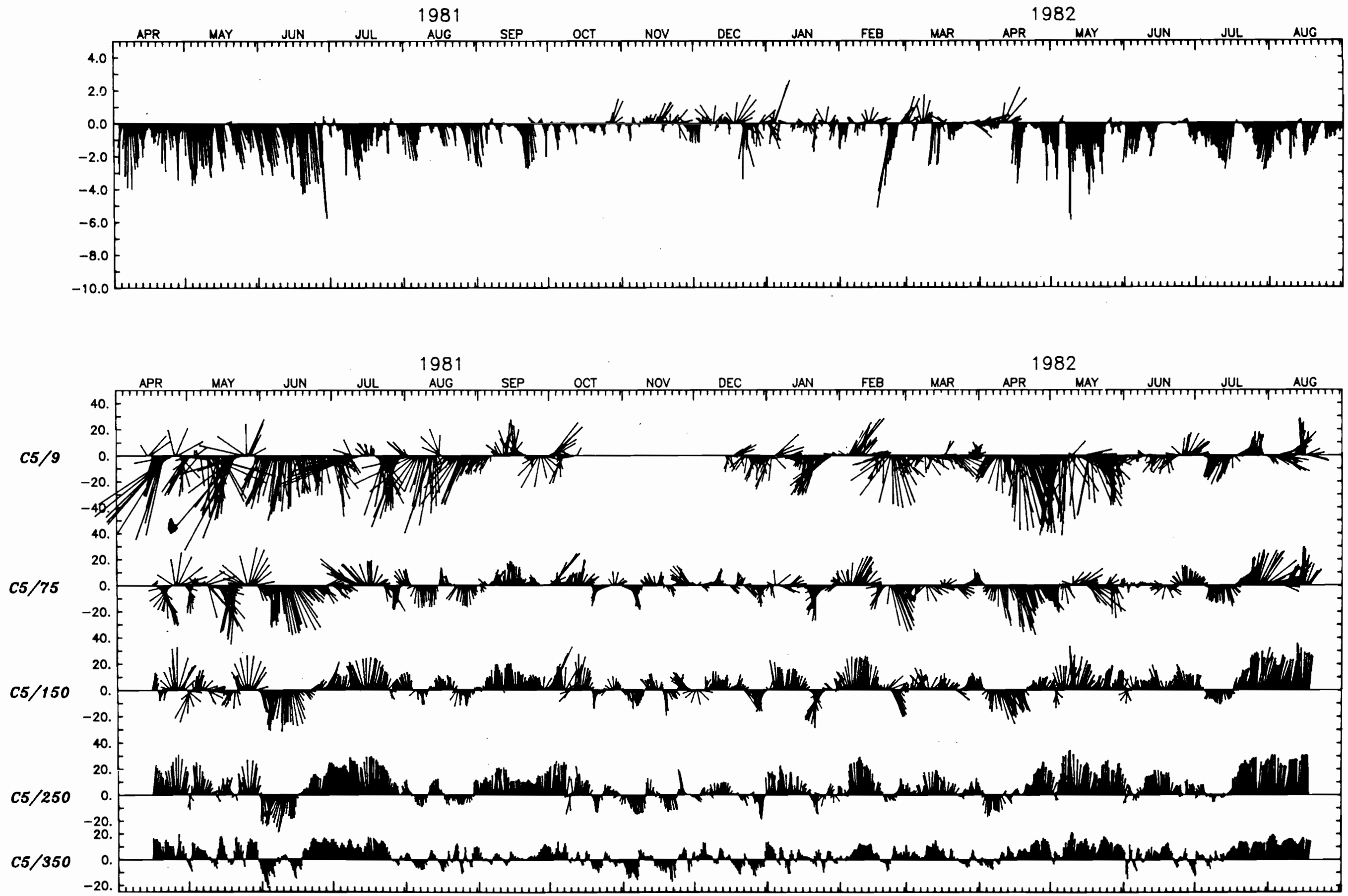

Figure 6: Time series of 12-hourly low-passed (<0.6 cpd current vectors at the CODE C-5 mooring over the 400 m isobath at 38°31'N, 123°40'W from April 1981 to August 1982. Low-passed vectors of wind stress are shown at the top. Vectors are oriented so that 335°T is at the top of the page and 65°T is to the right.

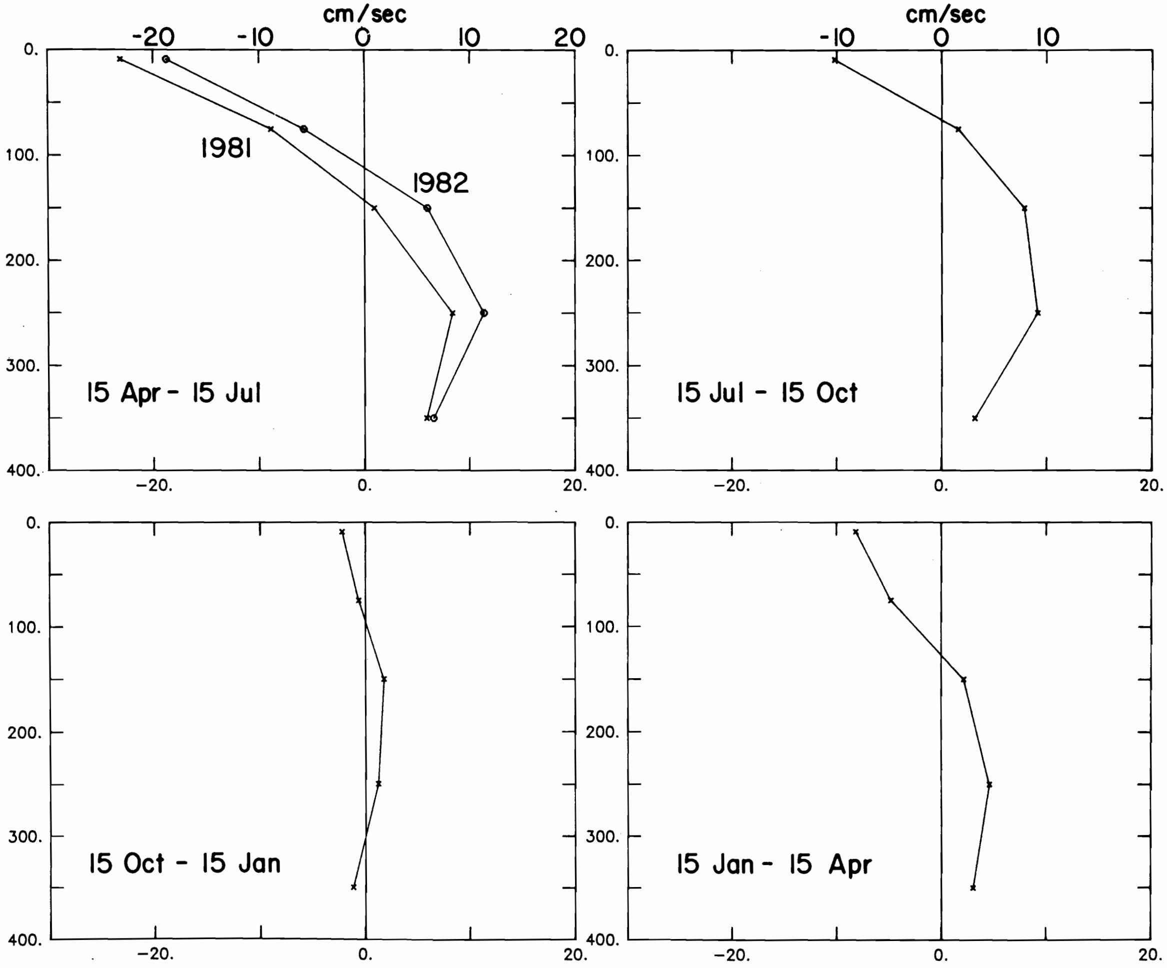

Figure 7: Vertical profiles of the three-month average along-shore current (positive toward 335°T) at C-5.

Table 1. Overall means and standard deviations of the current and temperature at the C-5 mooring.

Direction of Major Axis			Onshore Current (65°T)		Along-shore Current (335°T)		Temperature		
Depth	N	(°T)	mean	std dev	mean	std dev	mean	std dev	N
9	1717	317	-1.1	13.1	-12.8	18.8	11.30	1.18	1968
75	1960	337	2.9	7.3	-2.6	12.7	9.75	0.81	1960
150	1959	333	1.2	4.4	5.0	12.3	8.48	0.13	1959
250	1960	335	0.4	2.0	8.1	11.9	7.84	0.11	1960
350	1959	338	0.5	0.3	4.2	7.5	7.08	0.07	1959

Table 2. Three-month means and standard deviations of the onshore (65°T) and along-shore (335°T) components of the current at C-5.

	15 Apr- 15 Jul 1981		15 Jul- 15 Oct 1981		15 Oct- 15 Jan 1982		15 Jan- 15 Apr 1982		15 Apr- 15 Aug 1982	
depth	mean	std dev	mean	std dev	mean	std dev	mean	std dev	mean	std dev
u 9	-6.0	18.8	-4.9	10.0	(2.7)	(9.1)	-0.6	11.3	2.5	9.8
75	+4.2	10.5	1.2	4.8	1.3	5.4	1.5	7.5	3.6	5.9
150	1.6	5.2	0.4	3.4	0.6	4.4	1.6	5.2	1.0	3.8
250	0.3	2.8	0.0	1.4	0.7	1.8	0.7	2.0	0.3	1.7
350	0.0	1.1	0.1	0.9	0.6	0.7	0.5	0.8	0.6	0.8
v 9	-22.8	18.3	-10.2	19.3	(-6.3)	(8.3)	-8.0	13.8	-18.9	20.0
75	-9.2	15.5	1.6	10.5	-0.6	7.5	-4.6	11.5	-6.0	11.0
150	0.7	14.6	7.9	9.4	1.8	9.4	2.3	12.4	5.9	10.0
250	8.2	14.6	9.3	9.9	1.2	3.0	4.6	3.0	11.4	9.7
350	5.9	8.7	3.2	6.1	-1.2	2.1	3.0	1.6	6.5	6.6

it is strongest during the upwelling season and that it disappears or merges with the Davidson Current in winter. We also think that its core occurs at different depths (and densities) at different latitudes, but this is really only a guess since simultaneous observations from different latitudes have only recently become available. We do not know what determines the undercurrent variability on time-scales of weeks which does not seem to be directly related to variations in the wind. With so little known about the structure and variability of the undercurrent, we obviously do not know how it is forced.

CONCLUDING REMARKS

There is a great deal we still do not understand about the undercurrent that flows poleward along the continental slope off California and the Pacific Northwest. Many questions remain: Is the undercurrent continuous along the coast? What determines the width, strength, and the core-depth of the undercurrent? How and why do these vary with location and from season to season? Are the northward-tending tongues seen in water property distributions due primarily to advection, or are mixing and interleaving more important? Is the poleward flow observed near the bottom over the outer shelf merely a manifestation of the slope undercurrent, or is it an independent phenomenon with its own characteristics and forcing mechanism? We hope that these and other questions about undercurrents will be addressed by an integrated program of additional observations and improved models in the decade to come.

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