

Characteristic patterns of shelf circulation at the boundary between central and southern California

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Received 15 January 2002; revised 25 September 2002; accepted 6 November 2002; published 6 February 2003.

[1] The coastal circulation in the Santa Barbara Channel (SBC) and the southern central California shelf is described in terms of three characteristic flow patterns. The *upwelling pattern* consists of a prevailing equatorward flow at the surface and at 45 m depth, except in the area immediately adjacent to the mainland coast in the SBC where the prevailing cyclonic circulation is strong enough to reverse the equatorward tendency and the flow is toward the west. In the *surface convergent pattern*, north of Point Conception, the surface flow is equatorward while the flow at 45 m depth is poleward. East of Point Conception, along the mainland coast, the flow is westward at all depths and there results a convergence at the surface between Point Conception and Point Arguello, with offshore transport over a distance on the order of 100 km. Beneath the surface layer the direction of the flow is consistently poleward. The *relaxation pattern* is almost the reverse of the upwelling pattern, with the exception that in the SBC the cyclonic circulation is such that the flow north of the Channel Islands remains eastward, although weak. The upwelling pattern is more likely to occur in March and April, after the spring transition, when the winds first become upwelling favorable and while the surface pressure is uniform. The surface convergent pattern tends to occur in summer, when the wind is still strong and persistently upwelling favorable, and the alongshore variable upwelling has build up alongshore surface pressure gradients. The relaxation pattern occurs in late fall and early winter, after the end of the period of persistent upwelling favorable winds. *INDEX TERMS:* 4516

Oceanography: Physical: Eastern boundary currents; 4219 Oceanography: General: Continental shelf processes; 4532 Oceanography: Physical: General circulation; *KEYWORDS:* coastal circulation, upwelling, Santa Barbara Channel, bio-geographical boundaries, transport pathways

Citation: Winant, C. D., E. P. Dever, and M. C. Hendershott, Characteristic patterns of shelf circulation at the boundary between central and southern California, *J. Geophys. Res.*, 108(C2), 3021, doi:10.1029/2001JC001302, 2003.

1. Introduction

[2] The poleward flow along the coast of central California has been known to exist at least since *Marmor* [1926]. *Sverdrup et al.* [1942] call this inshore surface counter current the Davidson Current (DC), and *Schwartzlose* [1963], reporting on the trajectories of surface floating drift bottles released along the California coast, concludes: "The predominant feature exhibited by the drift bottles. . . is the counter current during the fall, winter and early spring months from central California to British Columbia. By October it appears as far south as Point Conception. . . The important unique features. . . are its narrowness compared to its length (a ratio of 1/20) and its ability to carry drift bottles at speeds over 0.5 knots for long distances before they come ashore." The presence at the surface of the DC is noted in compilations of the California Cooperative Fisheries Investigation (CalCOFI) observations [*Hickey*, 1979; *Lynn and Simpson*, 1987]. *Strub et al.* [1987a] report observations of currents over the continental shelf and slope between 35°N

and 48°N, and show that annual average near bottom currents are poleward everywhere. At 35°N, the annual average currents at 35 m are also poleward, opposing the annual average wind stress.

[3] *Kolpack* [1971], *Brink and Muench* [1986], and *Harms and Winant* [1998] (hereafter HW98), among others, have shown that over the mainland shelf in the Santa Barbara Channel (SBC), water flows westward out of the channel at the surface and at mid-depth nearly all the time (Figure 1), so that at least a fraction of the DC transits through the SBC. In contrast, the time-averaged surface flow along the central California coast cannot simply be described as a permanent poleward current because, north of Point Arguello and near the surface, the time-averaged velocity is equatorward, consistent with upwelling favorable wind stress, and in the opposite direction from the flow at 35 m depth and beneath.

[4] The results presented here extend the spatial coverage of the synoptic description given in HW98. The central new result is an improved description of shelf and slope flow inshore of the equatorward California Current (CC), generally most intense 50 to 100 km from the coast, that emphasizes the opposite direction of the flow near the surface relative to that in deeper layers, where the direction

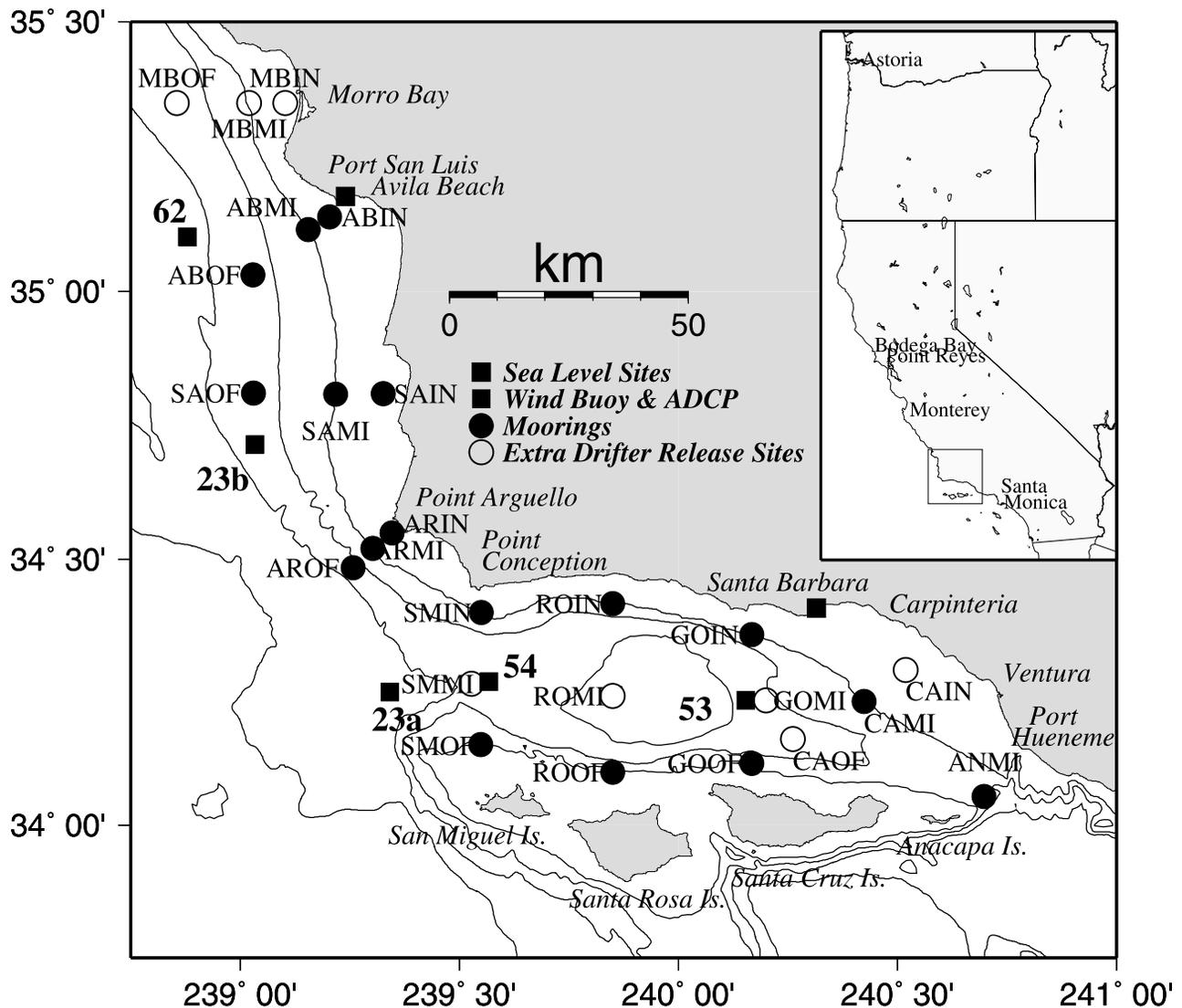


Figure 1. Moorings, sea level station locations, and drifter release sites. Contours of the 100-, 250-, 500-, and 1000-m isobaths are drawn. National Data Buoy Center buoys are designated by their last two numerals. Mooring transects north of Point Conception are designate by AB (Avila Beach), SA (Point Sal), and AR (Point Arguello). Drifters were released at all mooring sites except ANMI, as well as at the locations indicated by the open circles.

is poleward most of the year. In particular, an area of surface current convergence is identified between Points Arguello and Conception during summer and fall that results in vigorous offshore transport of shelf waters. This flow is eventually entrained into the California Current. The surface convergence is similar in some regards to the area of convergence observed off of Cape Blanco, in Oregon, by *Barth et al.* [2000].

[5] Moored observations spanning a number of years are used to describe the annual average and seasonal cycle of the flow in this complex area (section 3), and to show that the seasonal cycle can be described in terms of three characteristic circulation patterns. In section 4, surface drifter releases are used to provide examples of the different patterns. While elucidation of the detailed response of currents to synoptic scale wind-forcing is beyond the scope of this paper, it is shown in section 5 that the three patterns

can be used to represent the flow on timescales as short as a few days, and that they are qualitatively consistent with wind stress and a seasonally variable DC.

2. Observations

[6] The area of interest separates the Southern California Bight from the central California coast (Figure 1). In this region, the coastline undergoes a sudden change in direction between Point Conception and Point Arguello. East of Point Conception, the SBC basin is bounded to the north by the coast of mainland California, oriented approximately east-west, and to the south by the four channel islands. The channel is about 100 km long and 40 km wide, with a central basin depth of 500 m, and narrow shelves, ranging in width between 3 and 10 km, on either side. The sills at the eastern and western entrances are 200 and 430 m deep,

Table 1. Santa Barbara Channel-Santa Maria Basin Moored Instrument Locations and Equipment^a

Acronym	Station Name	Latitude, N	Longitude, W	Deployed	Recovered	Depth, m	Instrument	
							Depth, m	Type
<i>Moorings</i>								
ABIN	Avila Beach Inshore	35°08'20"	120°57'36"	20 March 1996	15 Nov. 1999	35	...	...
ABMI	Avila Beach Middle	35°06'54"	120°50'42"	14 Jan. 1995	14 Nov. 1999	100	...	...
ABOF ^b	Avila Beach Offshore	35°01'50"	120°58'15"	20 March 1996	14 Nov. 1999	350	...	...
SAIN	Point Sal Inshore	34°48'30"	120°40'25"	21 March 1996	14 Nov. 1999	35	...	...
SAMI	Point Sal Middle	34°48'30"	120°47'00"	10 Dec. 1993	^c	100	...	...
SAOF ^b	Point Sal Offshore	34°48'30"	120°58'12"	20 March 1996	15 Nov. 1999	350	...	...
ARIN	Point Arguello Inshore	34°32'58"	120°39'15"	21 March 1996	17 Nov. 1999	35	...	...
ARMI	Point Arguello Middle	34°31'12"	120°41'50"	11 Jan. 1996	3 Nov. 1999	100	...	...
AROF ^b	Point Arguello Offshore	34°29'02"	120°44'31"	20 March 1996	3 Oct. 1999	350	...	...
SMIN	San Miguel Inshore	34°23'57"	120°27'00"	16 April 1992	^c	100	...	...
SMOF	San Miguel Offshore	34°09'17"	120°27'16"	24 April 1992	^c	100	...	...
ROIN	Rosa Inshore	34°25'04"	120°09'16"	15 Dec. 1993	12 Jan. 1996	100	All	All
ROOF	Rosa Offshore	34°06'16"	120°09'06"	16 Dec. 1993	12 Jan. 1996	100	1, 25, 65	T
GOIN	Goleta Inshore	34°21'28"	119°50'24"	27 Oct. 1992	13 Jan. 1996	100	5, 45 (100 ^d)	VMCM, T, C
GOOF	Goleta Offshore	34°07'05"	119°50'58"	26 Oct. 1992	13 Jan. 1996	100	100 (200 ^d)	BP, T, C
CAMI	Carpinteria Middle	34°13'52"	119°34'34"	27 Oct. 1992	13 Jan. 1996	100	...	...
ANMI ^d	Anacapa Middle	34°03'13"	119°18'16"	26 Oct. 1992	^c	200	...	...
<i>NDBC Buoys</i>								
NDBC 23a	NOAA NDBC 46023a	34°18'00"	120°42'00"	9 Feb. 1995	Sep. 30, 1996	640	All	All
NDBC 23b	NOAA NDBC 46023b	34°42'50"	120°58'06"	9 July 1997	^c	380	10+	W, AT, AP
NDBC 54	NDBC 46054	34°16'12"	120°25'59"	25 Aug. 1993	^c	430	1	T, ADCP
NDBC 53	NDBC 46053	34°13'59"	119°49'59"	6 Aug. 1993	^c	400	...	...
NDBC 62	NOAA NDBC 46062	35°06'10"	121°07'15"	8 July 1997	^c	400	...	...

^aVMCM, vector measuring current meter; T, temperature logger; C, conductivity cell; BP, bottom pressure sensor; W, anemometer; AT, air temperature sensor; AP, atmospheric pressure sensor; ADCP, Acoustic Doppler Current Profiler; NA, not applicable. All depths are in meters below the sea surface except for the meteorological observations where the plus refers to the height of the instrument above the sea surface or land. Deployment and recovery dates of the instruments are listed in columns 5 and 6.

^bMoorings deployed in 350 m depth have current meters at 5, 45, 100, and 200 m, and no bottom pressure sensor.

^cStill operating.

^dANMI is equipped with an additional VMCM at 100 m and a bottom pressure sensor at 200 m.

respectively. The passages between the islands are about 40 m deep. North of Point Arguello, the coastline is directed north-south, up to Avila Beach. The bottom topography there is characteristic of the northern and central California coasts: over the shelf, the bottom slopes to depths of about 200 m over a distance of 20 km. Farther offshore, over the slope, the depth increases more rapidly, reaching 500 m at a distance of 30 km from the coast.

[7] A total of 17 mooring sites were occupied for periods longer than 1 year. The mooring nomenclature is as follows: the first two letters correspond to the transect on which the mooring is deployed (AN for Anacapa, SM for San Miguel, etc.), and the following two letters (IN, MI, or OF) indicate the location relative to the coast. Thus, the inshore mooring on the Point Sal transect is SAIN. With the exception of a single mooring (ANMI), deployed on the sill at the eastern entrance to the SBC in 200 m depth, all other moorings in the SBC were deployed on the 100 m isobath. Poleward of Point Conception, moorings were deployed on three transects perpendicular to the local isobaths, in depths of 35, 100, and 350 m. Instruments deployed on each mooring included current meters, temperature, conductivity, and, except for the 350 moorings, bottom pressure sensors. Four moorings (ANMI, SMIN, SMOF, and SAMI) were deployed for over 6 years. Three of the meteorological buoys maintained by the National Data Buoy Center (NDBC) in support of this program were equipped with downward-looking 75-kHz acoustic Doppler current profilers (ADCPs). Two of these buoys (NDBC 23 and NDBC 53) occupied two different sites at different times. ADCP

observations are thus available from a total of five sites. The location, depth, and period of deployment of moorings is summarized in Table 1.

[8] The drifters used in this study are similar to those described by *Davis* [1985] with the modifications described by *Winant et al.* [1999]. Up to 24 release sites were used, half in the SBC, and the other half north of Point Conception (Figure 1). Drifters were released a total of 29 times, releases are numbered from 1 to 30, release 1 was a test release that is not included in this analysis. For the first 17 releases, drifters were deployed in the SBC only. Drifters were deployed at all 24 locations for most, but not all, of the subsequent releases. Details of the first 20 releases are summarized by *Winant et al.* [1999]. Details of the remaining releases are included in Table 2.

3. Mean Fields, Seasonal Cycles, and Characteristic Patterns

3.1. Mean Circulation

[9] Monthly averages of properties are estimated as the mean value of all observations made in each month. Annually averaged properties are then estimated as the mean of the monthly averages. The annual averages of temperatures at 1 m, and currents at depths of 5 and 45 m are illustrated in Figure 2. The standard error for the mean currents is estimated as the ratio of the standard deviation along the major axis of the current divided by the square root of the number of degrees of freedom. This error varies from mooring to mooring between 0.005 and 0.02 m s⁻¹.

Table 2. Drifter Release Dates and Descriptions for Releases 18–30^a

Release No.	Release Date	Number of Released Drifters	Number of Beached Drifters	Circulation Synoptic State
18	1 May 1996	21	6	Surface convergent
19	3 Aug. 1996	24	7	Upwelling
20	13 Sept. 1996	21	3	Surface convergent
21	17 Dec. 1996	24	12	Relaxation
22	21 March 1997	27	12	Upwelling
23	20 July 1997	26	16	Surface convergent
24	8 Nov. 1997	24	15	Relaxation
25	17 April 1998	24	7	Upwelling
26	1 July 1998	25	6	Surface convergent
27	27 Oct. 1998	22	2	Surface convergent
28	10 Mar. 1999	25	9	Upwelling
29	3 Sep. 1999	16	7	Surface convergent
30	11 Nov. 1999	25	10	Upwelling

^aAN equivalent summary for releases 2–17 is given by *Winant et al.* [1999].

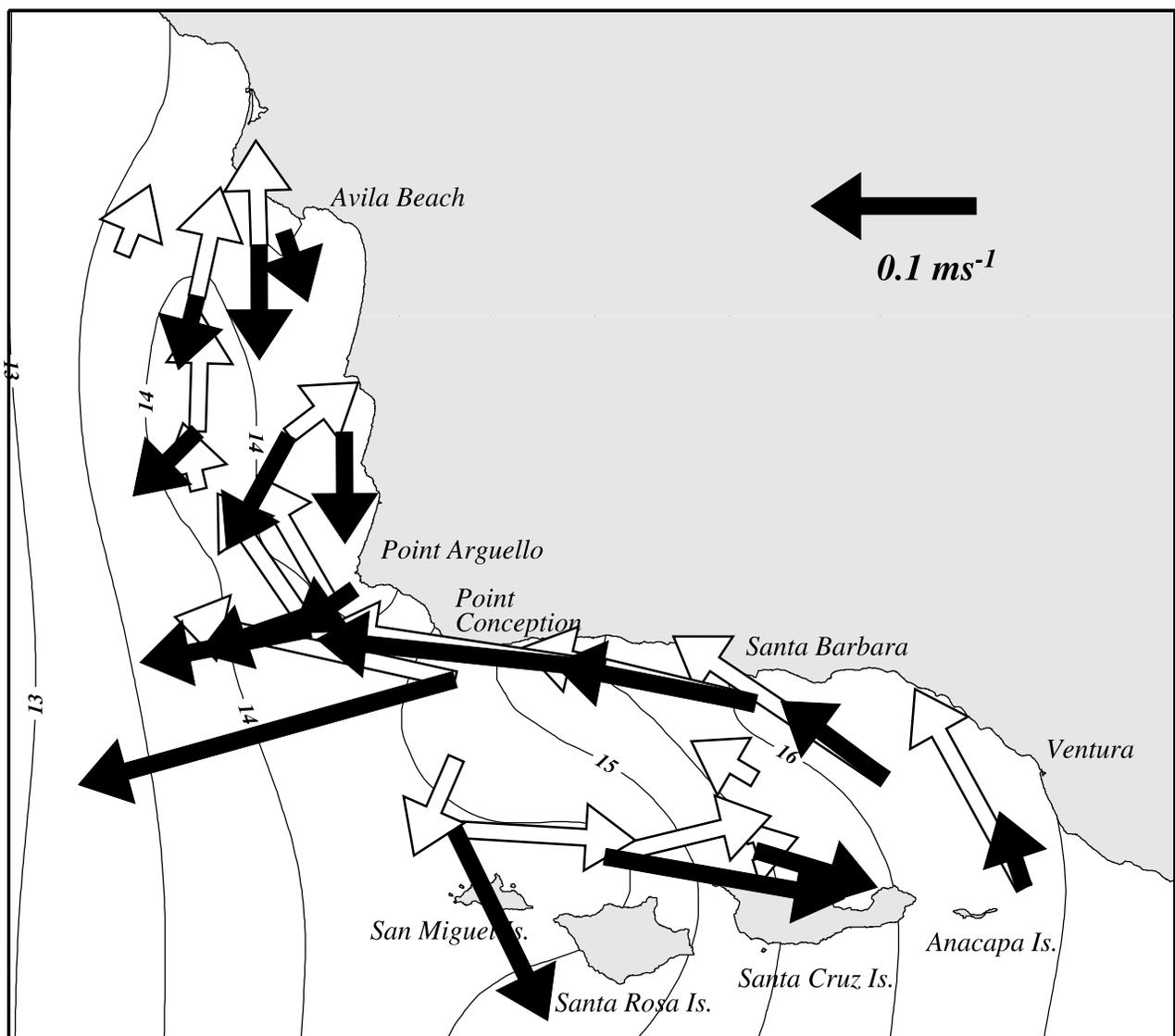


Figure 2. Contours of annual average temperatures (contour interval is 0.5°C), and currents at 5 m (solid vectors) and at 45 m (open vectors). The averages are computed as means of monthly averages. The deployment period is different for each mooring, and is identified in Table 1. All the mean vectors illustrated are larger than the standard errors, estimated as the standard error along the major axis divided by the number of degrees of freedom. The standard errors for the mean velocities are about 0.02 m s⁻¹.

The average current vectors illustrated in Figure 2 are all larger than the standard error.

[10] The average temperatures generally decrease from the southeast to the northwest. In the SBC, the average temperatures are colder on the southern shelf, and poleward of Point Conception. The coldest average surface temperatures occur at the coast, as expected in an active upwelling area.

[11] The annual mean circulation at 5 m depth in the SBC is almost the same as that described in HW98, even though the averages presented here are over a much longer time period. The flow consists of a westward flowing jet concentrated on the mainland shelf, and a weaker return flow on the southern shelf. Drifter observations [Winant *et al.*, 1999; Dever *et al.*, 1998] show that these two flows are the opposite sides of a mean cyclonic circulation in the channel. Mean westward currents at 5 m strengthen between the eastern entrance and Point Conception (SMIN). North of Point Arguello (AB and SA lines), mean vectors are toward the south and southwest with largest amplitudes along the 100 m isobath. This near surface equatorward flow and the westward flow out of the SBC converge near Point Arguello, as evidenced by the flow along the AR line. The average near surface flow at the AR line is directed perpendicular to isobaths, an unusual feature in observations of coastal circulation.

[12] In the SBC, the mean flow at 45 m depth is qualitatively similar to the near surface flow, with a persistent westward direction along the mainland coast. The velocities associated with this flow exceed near surface values in the eastern portion of the channel. On the southern shelf, the 45 m flow is more closely aligned with the topography than the near surface flow, particularly near the western entrance (SMOF). At Point Arguello and poleward, the flow differs from the near surface flow both in magnitude and in direction. On the AB and SA transects, the mean flow is in the opposite direction from the 5 m flow. On the AR line, the mean flow at 45 m is parallel to the isobaths. There is no evidence at 45 m for flow convergence like that at 5 m, instead the sense of the mean vectors is of a continuous along isobath current flowing westward along the mainland coast in the SBC, turning around Points Conception and Arguello, and continuing, in the same sense as the DC, along the southern coastline of central California.

3.2. Seasonal Cycle

[13] The seasonal cycle of surface temperature and currents at 5 and 45 m depth is illustrated in Figure 3, with a sequence of maps representing 2-month averages of the variables. The 2-month period was chosen because individual monthly averages change little over that period, but differences between the 2-month averages are substantial. The standard error for currents averaged over a 2-month period is estimated as the ratio of the standard deviation along the major axis of the current divided by the square root of the number of degrees of freedom. This error varies from mooring to mooring between 0.02 and 0.04 m s⁻¹. Most of the current vectors illustrated in Figure 3 are larger than the standard error.

[14] The temperature maps show how the surface temperature gradients increase in the course of the season, from relatively isothermal in winter (the largest temperature difference is just over 1°C in January–February), to strong

gradients in late summer (near 5°C in July–August). In the summer months, the pool of relatively warm water that flows out of the SBC extends up the coast toward Avila Beach, separated from the coast by a pool of colder water, presumably associated with local upwelling.

[15] Bimonthly averages of currents at 5 m beneath the surface vary markedly depending on location. HW98 already noted that similarities existed between the cycles at ANMI and at SAMI, both being directed equatorward in spring, and reversing to poleward during the winter. Within the SBC, the direction of near surface currents does not change in time as much: at SMIN the monthly averaged currents are persistently westward, at SMOF the surface currents are persistently toward the southeast. In the same way, monthly mean currents at 5 m depth observed at the shallowest moorings (total depth of 35 m), north of Point Arguello (AB and SA lines) are consistently toward the south. The rich spatial structure of the annual cycle of currents 5 m beneath the surface is a notable feature of the circulation in this area. The variation in direction of currents along the AR line, toward the south in spring, at the height of the upwelling season, turning toward offshore during the summer, when the westward flow out of the channel intensifies, then becoming parallel to the coast in winter, in the opposite direction from spring, is remarkable.

[16] The annual cycle of currents at 45 m differs depending on location as well. In the SBC the direction changes little over the course of the year except where the monthly mean currents are weak, as at NDBC 54 and GOOF. North of Point Arguello, monthly means are for the most part poleward, but reverse direction briefly during the spring. The most striking difference between near surface and 45 m currents is off Point Arguello, where the current at 45 m persists in the poleward direction, in contrast to the variable direction near the surface noted above.

[17] Bimonthly averages of currents measured at the NDBC moorings, in water depths of 300 to 400 m, are illustrated in Figure 4. The cycle is consistent with that described above for currents observed at 45 m: most of the year the direction of the flow is poleward. The weakest averages are in January and February. In March and April, persistent upwelling favorable winds drive an equatorward current with maximum amplitude near the surface. The subsurface onshore circulation is clearly illustrated at the NDBC 62 and NDBC 23a sites at the same time. After June, the flow direction reverses in nearly the entire water column. The core of the poleward current is confined in the upper 200 m of the water column. From July through October the surface convergence results in weak surface velocities near NDBC 23a, explaining the subsurface speed maximum at that site. While the ADCP observations do not extend above 24 m beneath the surface, the vertical trends of currents at NDBC23b and NDBC 62 suggest that the poleward flow may extend all the way to the surface at their distances from the coast (about 20 km), as early as July.

3.3. Characteristic Patterns

[18] While the bimonthly averages illustrated in Figures 3 and 4 are complex, their major features can be summarily described in terms of three principal patterns, effectively represented by the flows observed in March and April, in July through September, and in November and December.

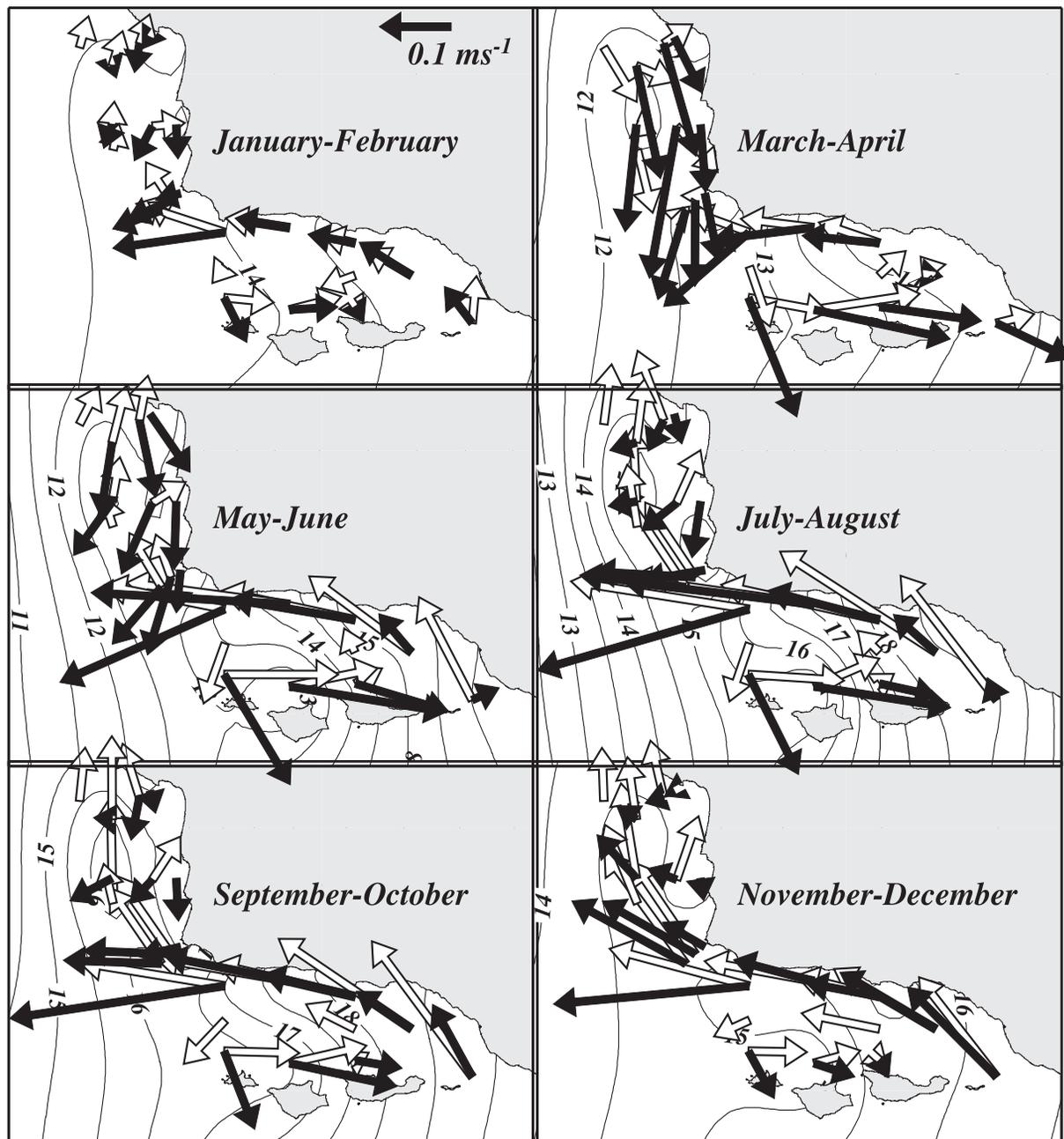


Figure 3. Bimonthly maps of contours of 1 m temperature (contours are 0.5°C apart), with 5 m currents (solid vectors) and 45 m currents (open vectors). The quantities are computed as the average of all measurements during the 2-month period. The standard errors of the mean speeds range between 0.02 and 0.05 m s^{-1} .

These patterns, computed as averages over the periods just enumerated, are illustrated in Figure 5.

[19] The spring, or upwelling pattern, consists of a prevailing equatorward flow at the surface and at 45 m, with the exception of the western portion of the mainland shelf in the SBC, where the cyclonic circulation persists in the form of a westward current. The southeastward flow near the surface at the eastern entrance (ANMI) and the weak eastward flow near the surface at CAMI only occur in this pattern, and this suggests that, in March and April, the net surface flow is out of the SBC toward the Southern California Bight. North of Point Conception, the circulation

corresponds to the description of the response of surface currents over the shelf to strong upwelling favorable winds as measured, for instance, during the Coastal Ocean Dynamics Experiment (CODE) [Winant *et al.*, 1987]. The upwelling pattern is the only instance where currents at 45 m are equatorward north of Point Arguello. The westward currents at that depth along the mainland coast of the SBC are about half the value found at other times.

[20] The major differences between the flow during the summer, the surface convergent pattern, and the spring upwelling pattern are the reversal of the flow at the eastern entrance to the channel at both 5 and 45 m, the reversal of

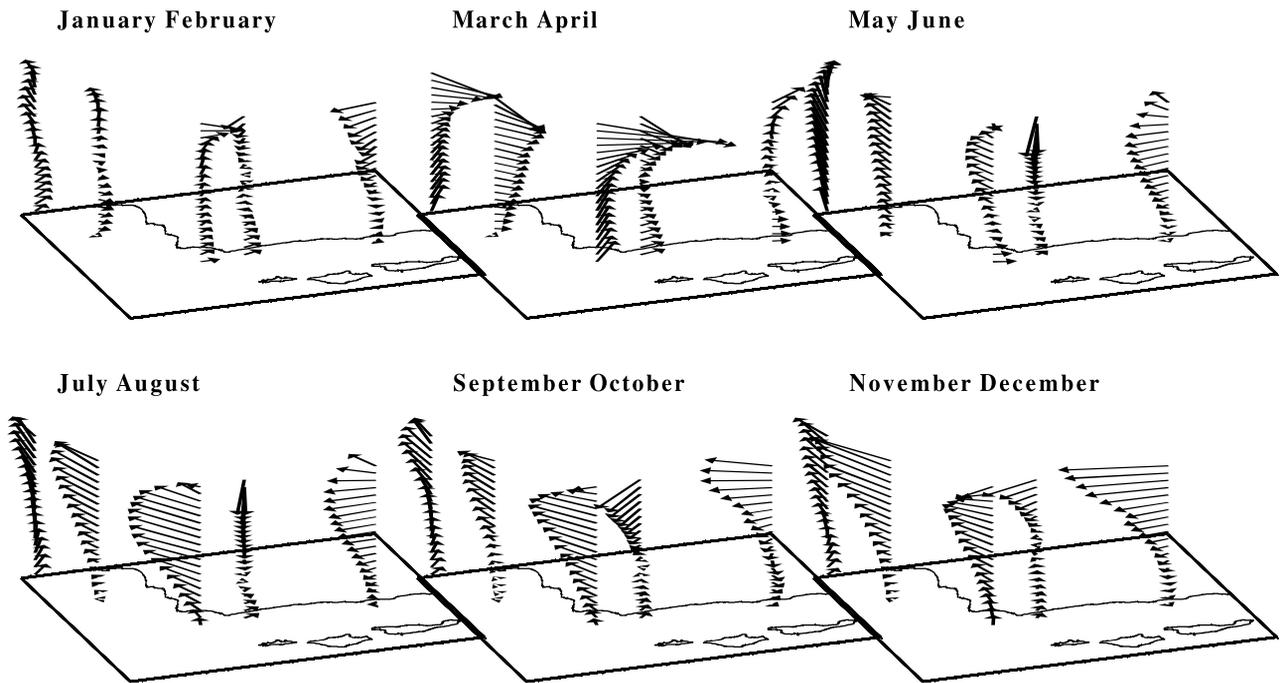


Figure 4. Bimonthly maps of the vertical structure of currents between 24 and 350 m beneath the surface. The observations are from NDBC buoys equipped with downward-looking ADCPs. The deployment period is different for each mooring, and is identified in Table 1.

the 45 m flow north of Point Arguello, and the weakened equatorward flow near the surface north of Point Arguello. These differences result in convergence near the surface at Point Arguello, with large surface currents toward the west

at all mooring sites in this area. The summertime poleward flow through the eastern entrance is much larger at 45 m than near the surface. The 45-m poleward flow follows the coast around Points Conception and Arguello, as if the DC

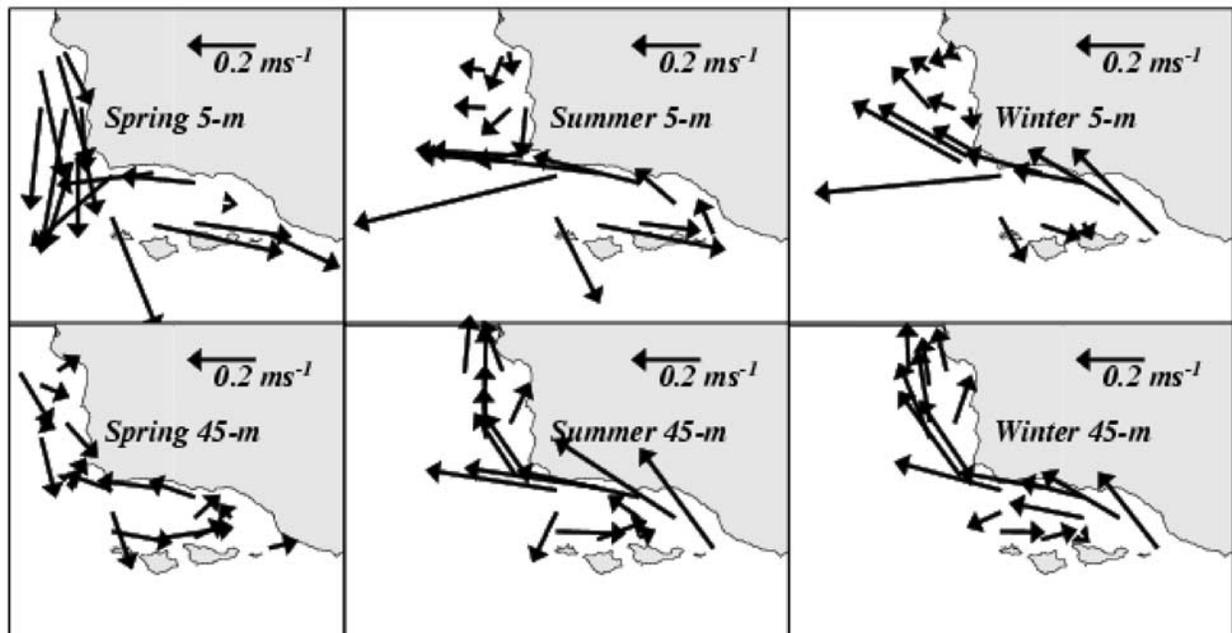


Figure 5. Three characteristic patterns of circulation at 5 m and at 45 m beneath the surface. The upwelling (spring) pattern is the average for March and April (left panels), the surface convergent (summer) pattern is the average for July, August and September (middle panels) and the relaxation (winter) pattern is the average for November and December (right panels). The standard errors of the mean speeds range between 0.02 and 0.05 m s^{-1} .

were already established at this depth. This subsurface poleward current has already been noted in observations at 35 and 65 m depth poleward of Point Conception, reported by *Strub et al.* [1987a]. The most conspicuous feature of the Surface convergence pattern is the very distinct nature of the circulation at 5 and 45 m. The summer pattern is similar to the mean flow, as illustrated in Figure 2.

[21] In the winter, corresponding to the relaxation pattern, the vertical differences between 5 and 45 m are less accentuated than in the summer. The surface flow at Point Arguello and to the north is poleward (although considerably weaker than currents at 45 m), with the exception of currents at the shallowest mooring sites, that continue to be equatorward, and suggest the possible existence of an anti-cyclonic circulation between the shore and the 100-m isobath, and between Point Arguello and Avila Beach. The weak eastward currents on the southern shelf of the SBC demonstrate the persistence of the cyclonic tendency in the area, even as the main flow becomes poleward.

[22] HW98 described the circulation in the SBC in terms of six patterns that correspond closely to the patterns described here. Their upwelling and flood east synoptic views correspond to the upwelling pattern proposed here. The cyclonic and propagating cyclone synoptic views are equivalent to the surface convergent pattern, and the relaxation and flood west synoptic views correspond to the relaxation pattern. The present paper identifies the surface convergence at Point Arguello and the existence of an offshore jet, as well as the vertically sheared flow north of Point Conception during the summer months.

4. Events: Surface Drifter Observations

[23] To this point the circulation has been described in terms of yearlong or monthlong averages based on moored observations. In this section, individual events that illustrate the relevance of the three patterns described above to time averages over event scales are described based on surface drifter trajectories. The trajectory of drifters is rich in small-scale features that are absent in the averaged patterns described above. This perspective is, however, limited by considerations of synopticity: drifters are tracked for periods up to 40 days, during which the prevailing circulation can switch from one pattern to another.

[24] In all, 29 sets of drifters were released in the area of concern here, between 1993 and 1999. *Winant et al.* [1999] report on the trajectories of the first 20 releases, in the SBC, and conclude that individual releases can be segregated in three general patterns that correspond to the three characteristic patterns described above. That conclusion is not changed by including the more recent releases to the data set. Four examples of releases corresponding to each of the three patterns are illustrated in Figure 6.

[25] The trajectories observed in the course of releases 7, 22, 25 and 28, provide examples of trajectories corresponding to the upwelling pattern, in different years. In each case, many drifters enter the Southern California Bight through the eastern entrance to the SBC. Drifters released north of Point Conception flow southward, some bypass the SBC entirely, and others flow through the SBC. In some, release 22 for example, the trajectories coalesce in two distinct groups, corresponding to those that avoided the SBC and

those that flowed through the SBC. In other cases, for instance release 25, the two groups of trajectories merge again south of the Channel Islands. Within the SBC, there are a number of examples of nearly closed cyclonic trajectories, with gradual westward movement of the trajectory center along the mainland shelf. Individual trajectories combine to form a broad swath in the Southern California Bight, and there are several examples of drifters running ashore on the mainland coast.

[26] Releases 9, 16, 18, and 26 provide examples of the surface convergent pattern. In each case, drifters released in the SBC leave the channel through the western entrance, after several cyclonic cycles. Drifters released north of Point Arguello drift southward where they encounter drifters from the SBC. The subsequent motion consists of complex cycles superposed on a westward drift at the latitude of Point Conception. The two streams, as marked by the trajectories, merge in an area that is about 100 km wide. Eventually the drifters become entrained in a southward flowing current, most likely associated with the CC, and drift southward. *Winant et al.* [1999] have noted that the trajectories remain closely grouped in the Southern California Bight over long periods of time, at least until the end of data transmission. *Brink et al.* [2000] describe the trajectories of three drifters that followed similar paths between late August and December, 1994. While those trajectories were farther offshore than the ones described here, the tendency for drifter trajectories to coalesce at this time of year can be taken, as *Brink et al.* [2000] suggest, as evidence for a high velocity core within the CC that coincides with a front that separates offshore from coastal waters.

[27] The relaxation pattern is illustrated by the trajectories of drifters deployed during releases 4, 5, 21, and 24. While a few drifters peel away from the core and eventually flow southward, the bulk of the poleward trajectories are concentrated in a band of width 40 to 50 km that extends up to Monterey Bay. Several drifters traveled considerably farther north, along the coast, a few were recovered in Bodega Bay, California and one was recovered from the bottom off Astoria, Oregon. The maximum distance drifters can travel north along the coast during this season is thus well in excess of 1000 km. *Brink et al.* [2000] describe trajectories of a large number of near-surface drifters deployed in the period 1993–1994, north of Point Arena, and note that “if a Davidson Current existed during 1993–1995, it was probably either short-lived or only found closer to the coast... within 100–150 km of shore.” The trajectories of drifters deployed in releases 4 and 5, confirm the existence of the DC at the time, located in the “void” described by *Brink et al.* [2000].

[28] The following description of three releases highlights individual features that do not appear in statistical compilations, or are masked in spaghetti diagrams of the kind illustrated in Figure 6. The complexity of the individual trajectories contrasts strongly with the relative simplicity of the characteristic patterns illustrated in Figure 5.

4.1. Upwelling: 17 April 1998 (Release 25)

[29] Fifteen drifters were deployed on 17 April 1998 (release 25), along the San Miguel line and all deployment sites to the north. The wind was upwelling favorable since the beginning of March, the wind stress reached 0.4 Pa on

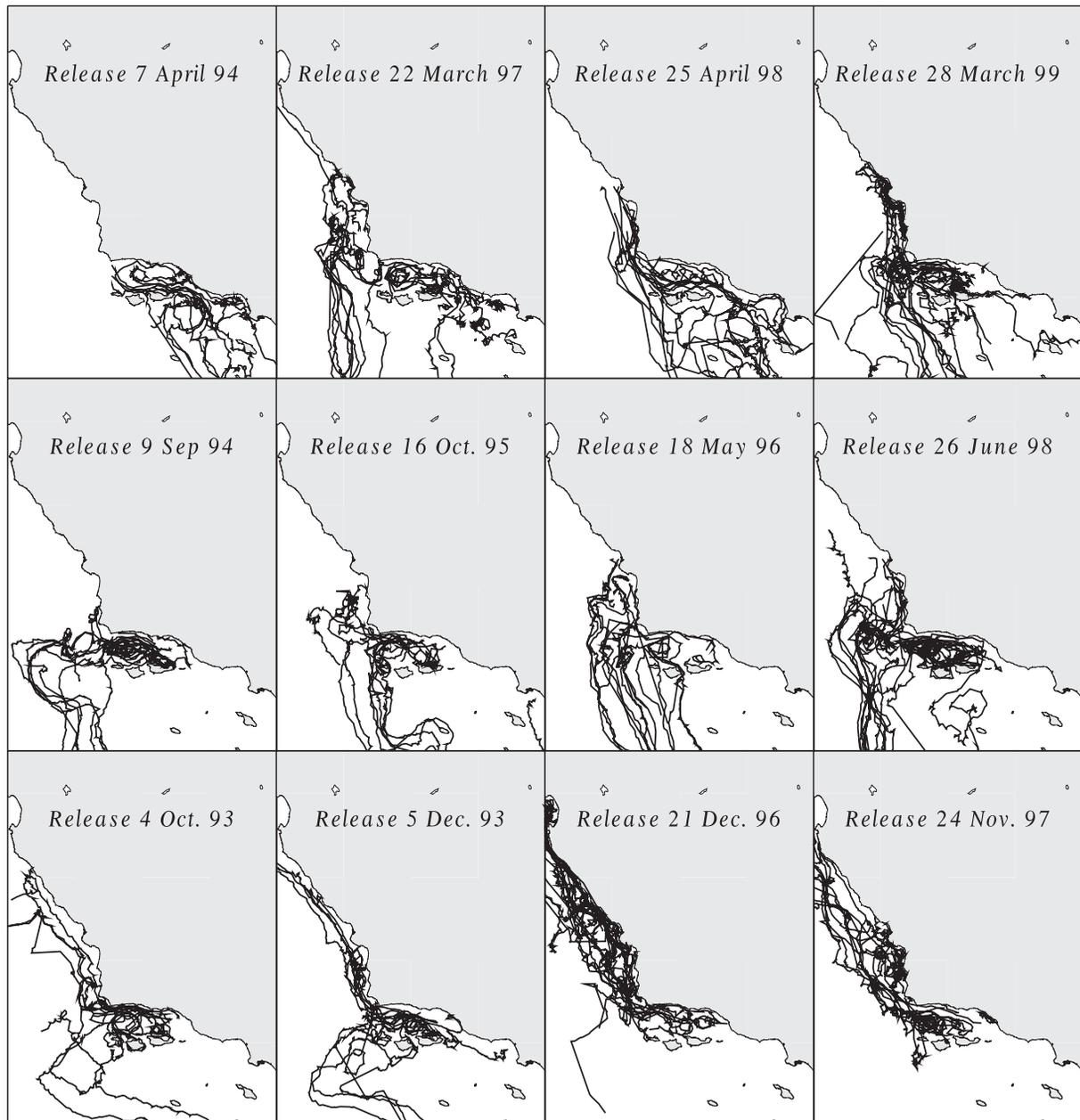


Figure 6. Examples of trajectories corresponding to three different characteristic patterns. The top row illustrates releases during March and April, when the upwelling pattern prevailed. In April 1994, drifters were only released in the SBC. The middle row includes examples of the surface convergent pattern. In September 1994, drifters were only released in the SBC. The bottom row illustrates releases when the relaxation pattern prevailed. In October and December 1993, drifters were only released in the SBC.

the day of deployment, relaxed on 21 April, and returned to upwelling favorable on 25 April. These different regimes combined to produce the drifter trajectories illustrated in Figure 7.

[30] Initially (17–21 April), all drifters migrate toward the south or southwest. Drifters released at the offshore locations (corresponding to a depth of 350 m) north of Point Arguello and the drifter released at SAMI avoid the western entrance to the SBC and enter the Southern California Bight directly. Drifters released at MBMI (middle site on the Morro Bay line), ABMI, ARMI transit through the channel in a few days, before the wind relaxes. This group of drifters

travels about 160 km in 4 days. The drifter released at SMOF beached on the neighboring San Miguel Island within 24 hours of release, and the drifter released at SMMI leaves the channel between San Miguel and Santa Rosa islands.

[31] Between 21 and 25 April, when the wind is calm, the drifter released at MBIN that had drifted south to Point Arguello in the preceding period, reverses course and runs aground just north of Point Sal. Two of the drifters that are in the SBC drift to the north and reverse course, toward the west. Three other drifters continue their eastern migration and eventually leave the SBC through the eastern entrance.

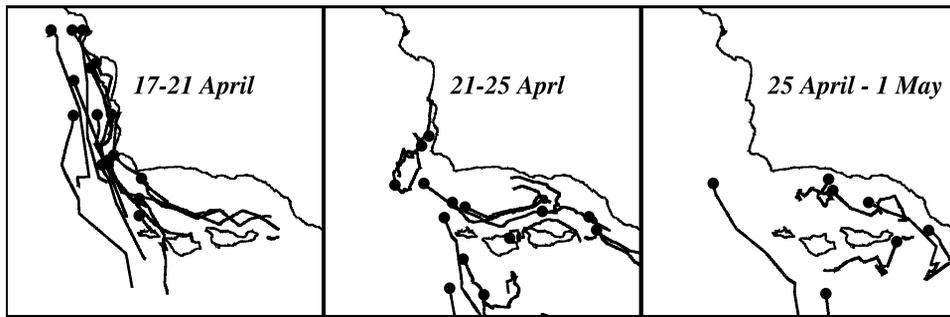


Figure 7. Drifter trajectories during release 25, illustrating the upwelling circulation pattern. The left frame corresponds to a period of strong equatorward winds, the middle frame corresponds to a period when the wind relaxed, and the right frame corresponds to a second period of equatorward winds. In this and following figures, the solid symbols correspond to the position of the drifter at the beginning of each period.

[32] The drifters released at SAIN and ARIN are entrained in complicated cyclonic movements after entering the channel. The drifter that was released at ARIN is transported back out through the western entrance at a time when the wind has relaxed, and runs aground near Point Sal, considerably north from where it was initially released. The drifter released at SAIN eventually makes it out of the channel, but only after having milled around in the SBC for a considerable period. The drifter released at AROF is an extreme example of the possible complexity of trajectories: during the initial period it enters the channel and drifts eastward very close to the islands, exiting the SBC through the passage between Santa Cruz and Anacapa. It then drifts westward along the southern side of the islands and reenters the channel between Santa Rosa and San Miguel and makes a full cycle in the channel before running aground on the north shore of Santa Rosa.

4.2. Surface Convergence: 1 July 1998 (Release 26)

[33] Most of the drifters in release 26 were deployed at the end of a period marked by strong upwelling winds that lasted until 5 July (Figure 8). Drifters released north of the Arguello line migrate south to the latitude of Point Arguello, where many are swept offshore and become entrained in presumably transient cyclonic circulation patterns for varying amounts of time. In contrast the drifter released at AROF moves rapidly toward the south with a path that crosses the trajectory of drifters released inshore on the same transect, at ARIN and ARMI. Drifters released east of Point Conception become entrained in the cyclonic circulation that is highly developed in the SBC in this season. The drifter released at SMIN moves south, along a path that is close to that of the AROF drifter. When the wind relaxes, on 5 July, the drifters are in three groups, one located 40 km southwest of Point Conception, another milling cyclonically in near the center of the SBC, and two drifters that are south of the latitude of the Channel Islands.

[34] During the 3-day period when the wind relaxes, the center of the cyclonic group in the SBC drifts about 20 km to the west, two drifters run aground on the north shore of Santa Cruz island, and the western group continues to cycle cyclonically.

[35] When the wind resumes, on 8 July, four of the drifters that were in the SBC run aground on San Miguel and Santa

Rosa island, two of the same group exit the SBC on a westward track and circle the western cyclonically trapped group before being entrained in the general southern drift.

[36] Two of the three drifters released off of Morro Bay on 5 July ran ashore near Point Sal and the third first drifted offshore before being entrained in the south flowing current.

4.3. Relaxation: 17 December 1996 (Release 21)

[37] Drifters were deployed at a time of variable winds, when anticyclones passed rapidly across the coast, causing the wind direction to change every few days. Synoptic conditions remained similar between 17 and 31 December, and the trajectories for this period are illustrated in Figure 9.

[38] All of the 12 drifters released on the Arguello line and to the north migrated toward the northeast, and reached the latitude of Monterey. Six entered and eventually ran aground in Monterey Bay. One, deployed at ABMI, transmitted positions as far as Point Reyes.

[39] Six of the 12 drifters released in the SBC followed similar trajectories to those released north. Of these, two (GOMI and SMMI) beached in Monterey Bay and two (SMOF and ROIN) ran aground north of Morro Bay. Two more migrated north, but backtracked after an episode of upwelling favorable winds on 1 January 2001. Two drifters (GOIN and ROOF) continued their westward course after leaving the channel, and one eventually started migrating south, and two more ran aground within the SBC. In all, 12 of the 24 drifters released ran aground.

5. Discussion

[40] The patterns presented in section 4 have synoptic timescales on the order of a few days. Over the course of a single drifter release, one or more transitions from one pattern to another may occur within the SBC-SMB region. However, the patterns, when averaged over months, lead to the well-defined seasonal cycles presented in section 3.2.

[41] To examine how the shifting probabilities of synoptic patterns lead to seasonal variability, we use the surface currents at the four locations maintained between December 1993 and November 1999 as an index of the characteristic patterns of upwelling, surface convergence and relaxation. Upwelling is defined to occur when flow (38 hour loss-passed to remove tidal variability) in the Santa Maria Basin

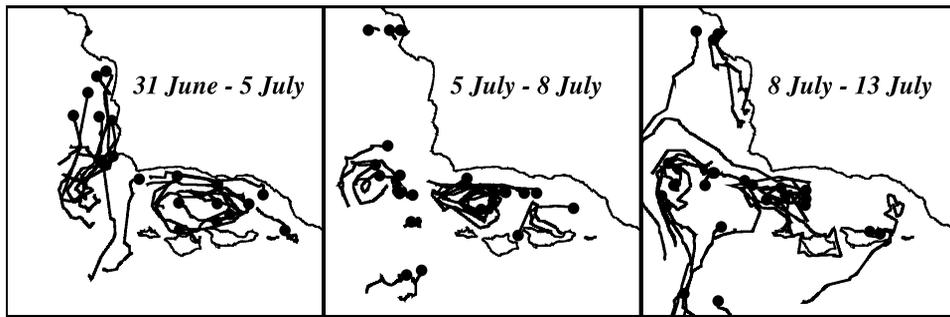


Figure 8. Drifter trajectories during release 26, illustrating the surface convergent circulation pattern. The left frame corresponds to a period of strong equatorward winds, the middle frame corresponds to a period when the wind relaxed, and the right frame corresponds to a second period of equatorward winds.

(SAMI) is southward and flow at the eastern entrance to the Santa Barbara Channel (ANMI) is southeastward. Surface convergence is defined to take place when subtidal flow in the Santa Maria Basin is southward, flow at the eastern entrance to the Santa Barbara Channel is northwestward, and flow at Point Conception (SMIN) is westward. Relaxation takes place when subtidal flow in the Santa Maria Basin is northward, flow at the eastern entrance to the Santa Barbara Channel is northwestward, and flow at Point Conception (SMIN) is westward. Only days with good velocity data at each of ANMI, SMIN, and SAMI are considered. There are also times when flow conditions do not satisfy any of the above criteria.

[42] The percentage of time during which the circulation corresponds to each of the three patterns is summarized for each month in Table 3. The results show that upwelling occurs primarily between February and June, Surface convergence occurs on almost any month (except April), and relaxation from September through January. Moreover, these three patterns, as defined above, account for approximately 87–97% of the record days in each month.

[43] When the drifter data are stratified by large-scale state (as determined from current meters), average current patterns deduced from the drifters are very similar to the patterns deduced from the moored observations. The characteristic flow patterns described here are based on the moored measurements because current meter observations are not biased in time, and therefore provide the best way to define the flow patterns. The drifter observations can be biased toward conditions that retain drifters in the study region. A comparison between spatial bin averages of the drifter velocities and current meter averages show that the drifter observations are biased away from the upwelling state in favor of the relaxation state. In the SBC this bias is not important, and the seasonal averages of the drifter observations compare well with the current meter results [Dever *et al.*, 1998].

[44] HW98 present an empirical orthogonal function (EOF) analysis for the period 1993–1995, when observations were concentrated in the SBC, and show that the upwelling and relaxation patterns are associated with the mode that accounts for most of the variance in the current observations, while the cyclonic pattern is associated with the second mode. A similar analysis of the extended observations presented here is similarly consistent with the three characteristic modes described above.

[45] Off Cape Blanco, on the Oregon coast, Barth *et al.* [2000] have found a flow structure that is somewhat similar to the surface convergence described here. Both off Cape Blanco and off Point Arguello, during the upwelling state, part of the equatorward flow of upwelled near surface water separates from the coast to form a coastal upwelling jet. Near Cape Blanco the near-surface jet remains equatorward. But equatorward from Point Arguello the surface flow in the SBC is nearly always westward. This convergence has no counterpart near Cape Blanco, so that the mechanisms underlying the separation at the two locations may be different. At undercurrent depths (greater than 100 m) flow is generally poleward at both sites. Hydrographic observations near Cape Blanco demonstrate the presence of undercurrent water offshore, under the offshore surface jet. No comparable observations are available for the Point Arguello area to locate the undercurrent.

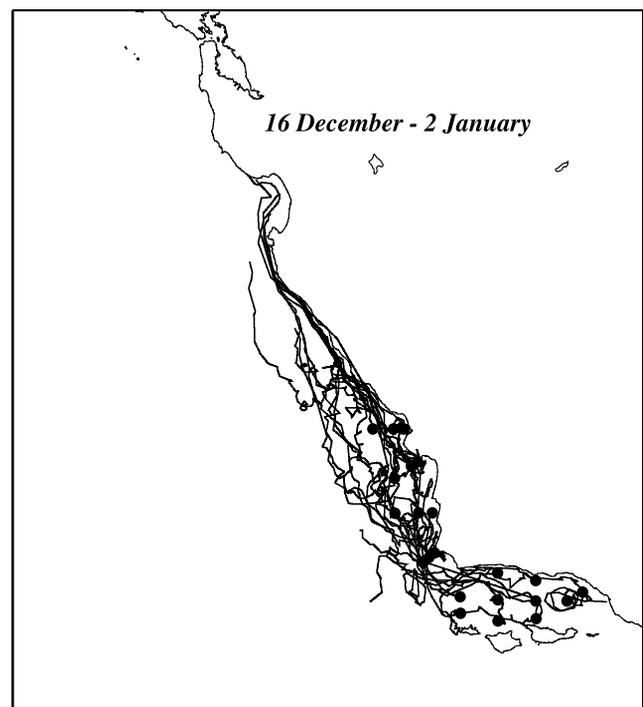


Figure 9. Drifter trajectories during release 21, illustrating the relaxation circulation pattern.

[46] Can the different circulation patterns described above be reconciled with what we know about the forcing of coastal flows in the area? The most persistent and best described feature of the coastal circulation between Los Angeles and Morro Bay is the Davidson or poleward inshore countercurrent described by *Marmor* [1926], *Sverdrup et al.* [1942], *Schwartzlose* [1963], and others thereafter. This current is in the opposite direction from, and so cannot be simply explained by the local wind stress. *Denbo and Allen* [1987] have noted that the dynamical forcing responsible for the poleward mean flow is not well understood. HW98 suggest that the forcing for this flow is related to the pressure difference between southern and central California. *Oey* [1999] proposes that the forcing is due to equatorward weakening of the wind curl. These two mechanisms are related: the weakening wind curl over large alongshore scales locally produces pressure differences such as described in HW98. The relaxation pattern described here is simply the local description of this large-scale flow.

[47] Within the SBC, HW98 stratified currents at 5 and 45 m by prevailing values of wind stress and along-coast pressure difference and identified the relaxation pattern as primarily driven by the along-coast pressure difference and the upwelling pattern as primarily driven by the wind stress. The very close similarity between three of the flow patterns given by HW98 and the patterns that come out of this analysis suggest similar dynamics govern those patterns. Both the general weakness of the wind stress during periods when the relaxation pattern is present, and the extension of the poleward flow at 5 m and particularly at 45 m all the way from the eastern SBC around Point Arguello and into the SMB suggest that the along-coast pressure force extends well around Point Arguello and into the SMB. The importance of the surface wind stress to the upwelling mode is suggested not only by the downwind component of the flow at both 5 m and 45 m in the SMB and along the southern shelf in the SBC, but also by the tendency of the 5-m flow to veer to the right of the 45-m flow.

[48] The cyclonic pattern identified by HW98, wherein the flow at SAMI and ANMI were in the opposite sense, and a strong cyclonic eddy was located within the western SBC is equivalent to the surface convergent pattern described in this analysis. HW98 suggested that the cyclonic mode came about when the wind stress and alongshore pressure gradient are of comparable magnitude, and it is reasonable to expect that the same forcing conditions generate the surface convergent flow. Equatorward wind stress over the SMB is consistent with surface equatorward and offshore flow, while a poleward pressure force is consistent with subsurface poleward flow in the SMB and westward flow along the northern shelf of the SBC, the two conditions that characterize the surface convergent pattern.

6. Summary

[49] The central result presented here is an improved description of shelf and slope flow inshore of the CC. This description emphasizes the vertical structure of the mean flow on the shelf and slope. Near the surface, at 5 m depth, the flow is equatorward, in the same direction as the wind stress. Beneath the surface, at 45 m depth, the flow is

Table 3. Probabilities of Each Characteristic Pattern Occurring in a Given Month^a

Month	Record Days	% Upwelling	% Convergence	% Relaxation	% None
Jan.	155	30	26	37	6
Feb.	141	52	26	19	3
March	154.5	53	34	2	11
April	150	86	9	3	3
May	155	48	32	15	5
June	150	45	33	17	5
July	155	22	32	33	13
Aug.	155	29	35	28	8
Sept.	152	20	36	38	6
Oct.	155	19	42	33	6
Nov.	135	5	34	53	8
Dec.	146.6	9	34	49	7

^aThe number of days available for each month is listed in column 2.

poleward, consistent with historical descriptions of the Davidson current. In the region between Morro Bay and the eastern entrance to the SBC, the circulation occurs most of the time in either of three principal patterns. The upwelling pattern consists of a prevailing equatorward flow at the surface and at 45 m depth, except in the area immediately adjacent to the mainland coast in the SBC where the cyclonic circulation is strong enough to reverse the equatorward tendency and the flow is toward the west. This is the only pattern in which flow enters the Southern California Bight through the eastern end of the SBC and the only pattern in which the flow at 45 m depth is equatorward north of Point Conception. In the surface convergent pattern the direction of flow reverses from surface to bottom north of Point Conception. Along the mainland coast, east of the point, the flow is westward at all depths and there results a convergence at the surface near Point Arguello that results in offshore transport over a distance on the order of 100 km. Beneath the surface layer the direction of the flow is consistently poleward. The relaxation pattern is almost the reverse of the upwelling pattern, with the exception that in the SBC, the cyclonic circulation is such that the flow north of the Channel Islands remains eastward, although weak. This pattern complements the description presented by *Brink et al.* [2000], by demonstrating the presence of the Davidson current along the shelf and slope.

[50] At the onset of the season of persistent upwelling favorable winds, in March and April, right after the spring transition [*Huyer et al.*, 1979; *Lentz*, 1987; *Strub et al.*, 1987b], the poleward circulation is weak or nonexistent, and the circulation develops in response to the wind stress, as observed in other coastal environments. The equatorward direction of flow extends down beneath the mixed layer, to at least 45m depth, and the transport through the SBC from the surface to 45 m is equatorward.

[51] As the upwelling season draws to an end, flow begins to enter the SBC from the southwest at 45 m and below in May. This poleward current flows more or less continuously along the mainland coast at depth. At the same time, the surface is forced by spatially variable wind stress in the same direction as the surface circulation in the surface convergent pattern: equatorward flow in the exposed areas north of Point Arguello and north of the Channel Islands, and poleward flow in the sheltered area along the mainland coast in the SBC.

[52] **Acknowledgments.** Support for this work was provided by Cooperative Agreement 14-35-0001-30571 between the Minerals Management Service and the University of California, San Diego. The authors are indebted to R. L. Smith who pointed out the Marmer [1926] and Schwartzlose [1963] references. CDW gratefully acknowledges the hospitality provided him by the Laboratoire d'Océanographie Physique at the Museum National d'Histoire Naturelle in Paris, and by Professor Maxence Revault d'Allones.

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