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Near-surface trajectories off central and southern California

C.D. Winant, D.J. Alden, E.P. Dever, K.A. Edwards, and M.C. Hendershott

Center for Coastal Studies, Scripps Institution of Oceanography, La Jolla, California

Abstract. The near-surface circulation in the Santa Barbara Channel and off the coast of central and southern California is described based on 20 releases of drifters drogued 1 m beneath the surface from 12 sites within the channel at bimonthly intervals. This description includes small-scale features of the circulation which are not part of descriptions based on moored observations or of the statistics of the drifter releases. The eventual fate of drifters at long time intervals compared to the residence time in the channel (about 7 days) is also included. In the channel the trajectories document a persistent cyclonic circulation with a typical recirculation period between 3 and 5 days. In the spring, currents near the mainland are weaker than near the Channel Islands, and the overall flow is toward the southeast. Trajectories document the possibility for water parcels to leave the channel through the interisland passes. In the late fall and winter a poleward flow with velocities often exceeding 0.5 m s^{-1} is confined within 20 km of the mainland. Between these two seasons the cyclonic tendency is enhanced, although most of the drifters eventually migrate westward. The trajectories of drifters released at the same time from sites only 20 km apart can be remarkably different. Once the drifters migrate out of the channel, their trajectories can be grouped into a few patterns. In spring and summer, drifters tend to remain in the Southern California Bight. Their trajectories often remain close over extended periods, as if they were caught in convergence zones. In fall the drifters often are caught in a poleward current.

1. Introduction

The Santa Barbara Channel (SBC, Figure 1) is bounded to the north by the mainland coast of California, which is oriented from east to west in this area. The four Channel Islands, San Miguel, Santa Rosa, Santa Cruz, and Anacapa, constitute the southern boundary. The passages between the islands are typically 40 m deep. The channel is about 100 km long and 40 km wide. The central basin extends to 500 m, and there are narrow, 3 to 10 km wide shelves on either side. The eastern sill has a depth of 220 m, and the depth at the western sill is 400 m.

The circulation of coastal waters in the SBC and neighboring areas was first described in 1969, as part of surveys done in the aftermath of the Santa Barbara Channel oil spill. On the basis of three hydrographic cruises conducted in May, August, and December 1969 and eight drifter card surveys, *Kolpack* [1971] presented maps of the near-surface circulation in the SBC. The most important features of these maps are a cyclonic cell located in the western half of the channel and northwestward flow present in the eastern section. The maps also suggest a complex pattern of small eddies between these two areas. The Organization of Persistent Upwelling Systems (OPUS) experiment and the Santa Barbara Channel Circulation Study (1983-1984) were designed to study the response of the circulation to strong and spatially variable wind forcing. In the vicinity of Point Arguello and Point Conception, observations suggest that currents and water properties often respond to the wind in the classical sense: Increasing equatorward winds lead to colder surface temperatures and higher equatorward currents [*Brink,* 1983; *Huyer,* 1983; *Winant et al.,* 1987]. In the SBC the flow consists of eddies, jets, and fronts which are not persistently correlated with the local winds [*Atkinson et al.,* 1986; *Barth and Brink,* 1987; *Brink and Muench,* 1986; *Gunn et al.,* 1987; *Lagerloef and Bernstein,* 1988].

On a yearly average, winds in the channel are strong and equatorward southwest of a line running approximately between Point Conception and Santa Cruz Island, and weak everywhere else in the channel [*Brink et al.,* 1984; *Caldwell et al.,* 1986; *Dorman and Winant,* 1995; *Winant and Dorman,* 1997]. The SBC is also part of the transition zone where cold upwelled waters meet warm Southern California Bight waters of subtropical origin [*Chelton,* 1984; *Lynn and Simpson,* 1987]. The different water properties can lead to surface pressure differences which may have a dynamical role in forcing

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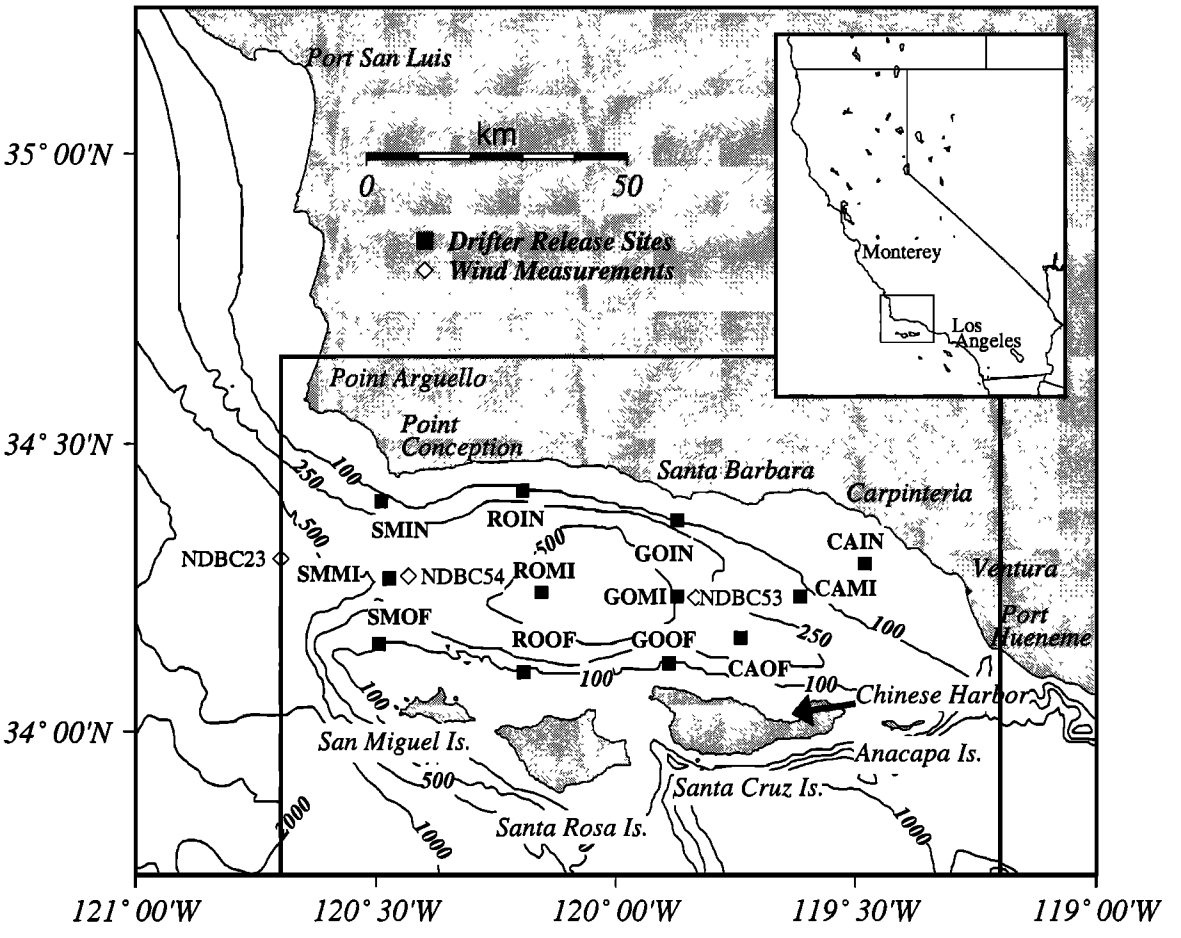

Figure 1. Santa Barbara Channel - Santa Maria Basin Coastal Circulation Study (SBC-SMB CCS) location map. NDBC buoys are designated by NDBCxx, where xx refers to the last two digits of the buoy number. The boxed-in area in the center of the map represents the area used for residence time calculations. Contour depths are in meters.

the circulation [*Hickey,* 1992; *Lentz and Winant,* 1986].

Radio-tracked drifters were used during the Coastal Ocean Dynamics Experiment (CODE) to identify for the first time features such as jets and squirts [*Davis,* 1985] as important processes in the cross-shelf exchange of water. A central advantage of drifters is that they can unambiguously show closed horizontal circuits.

In 1992 a multiyear program, the Santa Barbara Channel - Santa Maria Basin Coastal Circulation Study (SBC-SMB CCS) sponsored by the Minerals Management Service (MMS), was initiated with two objectives. The first was to describe the flow and develop simple dynamical relationships between it and the forcing mechanisms to guide the implementation of numerical models. The second objective was to summarize these descriptions in a manner useful to analysts who are charged with assessing what might happen in the event of an oil spill.

There are two motivations for this paper. The first is to complete the descriptions of the SBC circulation by documenting small-scale features which are lost in descriptions based solely on moored observations, for which the statistically significant empirical orthogonal functions (EOFs) capture only a fraction of the total variance [*Harms and Winant,* 1998] (hereafter HW98) or on statistics of the drifter measurements. The second is to document the eventual fate of drifters after they leave the study region, thus augmenting the available descriptions of the parcel motion along the California coast. The following section briefly describes the instruments, the configuration of the deployment array, and the schedule of deployments. The observed trajectories are presented in section 3. Residence times in the SBC and grounding events, when drifters went ashore, are described in section 4. The results are summarized in section 5. Throughout the paper, "poleward" and "equatorward" are used to denote the current directed along the coast with the mainland either on the right or on the left.

2. Observations

The observational period in the SBC extended from 1992 until 1996. The experiment consisted of five obser-

vational components. The first provided a description of the atmosphere over the area of interest; results are summarized by C.E. Dorman and C.D. Winant [*Dorman and Winant,* 1999]. Another component synthesized moored observations of currents and related physical parameters [*Harms and Winant,* 1998]. A third component was designed to provide spatially intensive snapshots of the circulation based on acoustic doppler current profiler (ADCP), expendable bathythermograph (XBT) and conductivity-temperature-depth (CTD) surveys conducted at regular intervals. The daily archiving of advanced, very high resolution radiometer (AVHRR) satellite imagery [*Hendershott and Winant,* 1996] constituted the fourth component. The fifth component, which forms the subject of this paper, provided a description of near-surface particle trajectories as a means of achieving both objectives of the experiment. A statistical and dynamical interpretation of these observations is presented in a separate paper [*Dever et al,* 1998].

The drifters used in this study were similar to those described by *Davis* [1985]. Briefly, the drifter consists of a submerged vertical tube inside which reside the electronics and batteries. An antenna protrudes from the top of the tube and extends up through the water surface. Four submerged cloth vanes of total area 1.8 m^2 extend radially from the tube. The entire assembly is attached to four flotation elements by short lengths of nylon line. Two modifications were made to the original design. The original cubic floats used to buoy the drifter to the surface were replaced by spheres of similar volume, and the buoys were equipped with a transmitter to locate the buoy using orbiting satellites and the Argos system. This system located the drifters up to six times each day, with a positional accuracy that varied between 150 m and 1000 m, depending on the quality of the fix. In a few cases the frequency of locations was reduced to a fix every few days.

Drifters were programmed to transmit for a period of 40 days following their release. Typically, trajectories consist of two stages: an initial period during which the drifter stayed inside the SBC area; and a final stage, when the path moved either into the Southern California Bight or off the coast of central California. These stages are described separately in the following section. Drifters were released approximately every 2 months at the locations shown in Figure 1. The locations were selected to coincide in most cases with current meter moorings, as described in HW98. Additional release sites were located between moorings so that the overall deployment scheme was spatially reasonably uniform. Deployments were not made within 20 km of the channel's eastern entrance, between Anacapa Island and Port Hueneme, since those drifters would have quickly left the area of interest at times when the current is equatorward.

The position of each drifter released as a function of time is available over the internet and can be viewed at the following address: http://www-ccs.ucsd.edu/research/sbcsmb/drifters.

Details of the drifter releases, dates, and instrumentation are included. There is also the capability to plot trajectories of any drifter or group of drifters. Animations of each drifter release can be viewed at the following address: http://www-ccs.ucsd.edu/research/sbcsmb/sat_images/movies.html.

3. Description of Trajectories

For each release, the date, the number of drifters released and beached, and the prevailing synoptic state of the circulation (as explained below) are listed in Table 1. There were about 5 releases each year, and the releases were approximately evenly spaced over the 4 year period.

3.1. In the Channel

Trajectories for each release within the SBC are compared in Figure 2. While no two releases were exactly the same, two general features can be identified in this comparison. The trajectories frequently suggest a cyclonic tendency within the channel. At times a net flow, averaged over the width of the channel, is superposed on the cyclonic circulation. In the spring the net flow is equatorward, and in the fall and winter it is in the opposite direction. These features combine to produce the following three patterns.

In several releases (for instance, 2, 6, 7, 11, 12, 13, 15, 17, and 19), after remaining for some time in the channel, the drifters migrate into the Southern California Bight, either through the eastern entrance, between Anacapa Island and Port Hueneme, or through

Table 1. Drifter Release Dates and Descriptions

Release	Release Date	Number of Drifters	Beached Drifters	Circulation Synoptic State
2	May 11, 1993	12	6	upwelling
3	July 26, 1993	15	5	cyclonic
4	Oct. 6, 1993	11	6	relaxation
5	Dec. 8, 1993	14	4	relaxation
6	Feb. 15, 1994	12	4	upwelling
7	April 13, 1994	12	8	upwelling
8	June 15, 1994	13	6	cyclonic
9	Sept. 13, 1994	14	6	cyclonic
10	Nov. 1, 1994	11	2	relaxation
11	Jan. 31, 1995	10	1	upwelling
12	March 16, 1995	11	1	upwelling
13	May 16, 1995	12	4	upwelling
14	July 7, 1995	11	5	cyclonic
15	Aug. 24, 1995	10	4	upwelling
16	Oct. 31, 1995	12	1	relaxation
17	Jan. 10, 1996	14	2	upwelling
18	May 1, 1996	11	4	cyclonic
19	Aug. 3, 1996	10	4	upwelling
20	Sept. 13, 1996	9	3	cyclonic
21	Dec. 17, 1996	11	2	relaxation

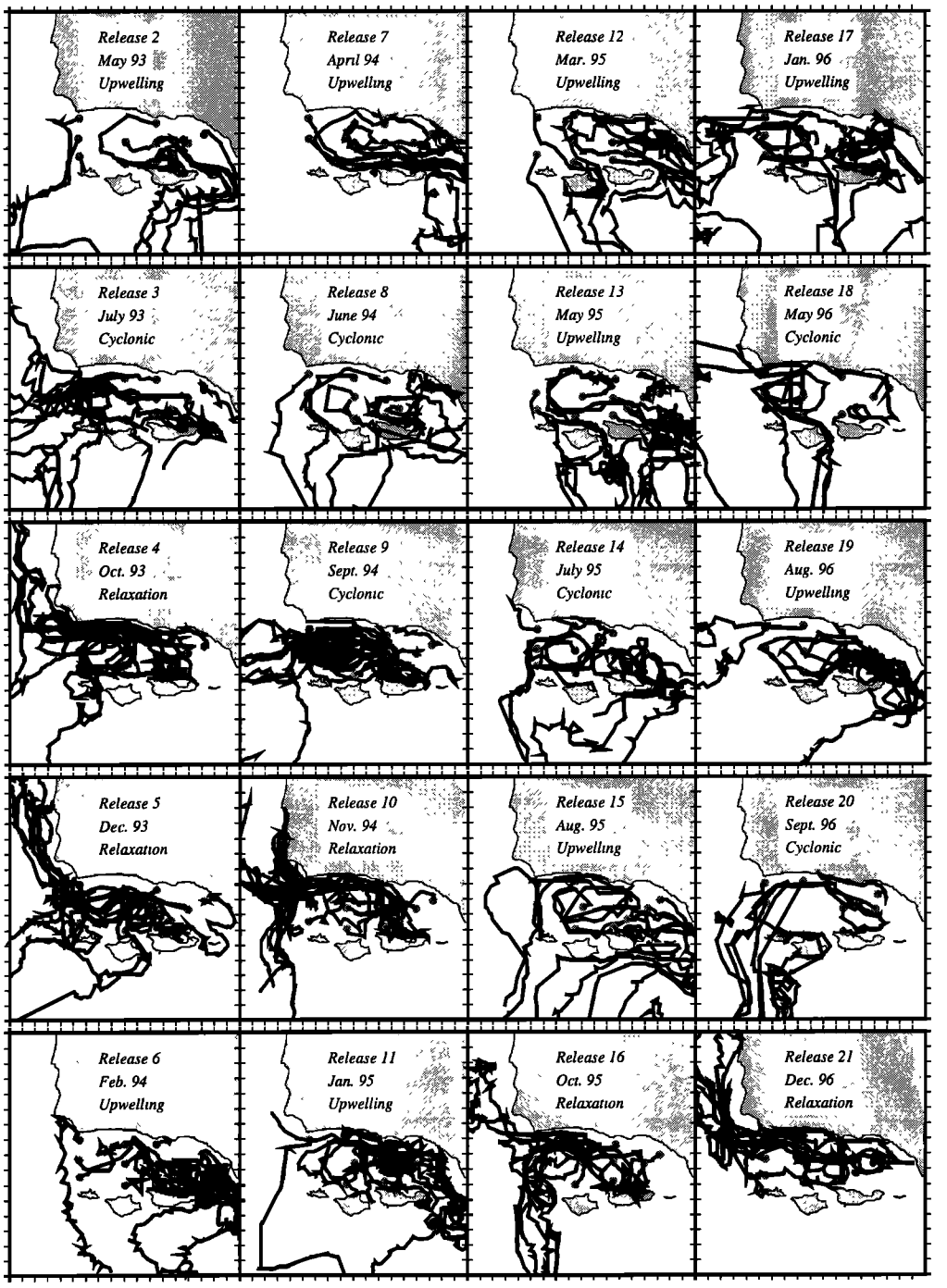

Figure 2. A comparison of drifter trajectories in each of the 20 releases. In the upwelling pattern, most drifters leave the channel either through the eastern entrance or through the interisland passes. In the relaxation pattern, many drifters travel along the coast poleward after leaving the channel. In the cyclonic pattern, drifters become entrained in a gyre in the western channel. Subsequently, they drift south toward the Southern California Bight.

the passes which separate the Channel Islands. This pattern is referred to as the upwelling pattern since it occurs more often in the spring and early summer, when the winds in the western portion of the channel and off central California become persistent and equatorward, conditions which are associated with upwelling off Point Conception.

In other releases (for instance, 4, 5, 10, 16, and 21) drifters seeded in the northeastern part of the channel are swept into a poleward current. Most of these trajectories are over the northern shelf. Beyond Point Conception, several of the drifters remain close to the coast, continuing poleward along the central California coast. Other drifters leave the channel through the western en-

trance, then drift toward the south. This pattern is thus not simply a reversal of the upwelling pattern, since trajectories often bifurcate upon leaving the channel. The relaxation pattern tends to occur more frequently in late fall and early winter, after upwelling episodes, when the equatorward winds have relaxed, and, for this reason, is called the relaxation pattern.

Some releases (for instance, 3, 8, 9, 14, 18, and 20) are characterized by an intense cyclonic circulation, with only weak flow out of the channel. This pattern is described as the cyclonic pattern. In some instances (notably releases 3 and 9) the trajectories suggest the presence of a cyclonic eddy which migrates toward the western entrance.

Grouping releases in terms of three principal patterns is consistent with the EOF analysis of the same observations described by *Dever et al.* [1998]. The first EOF mode, with a positive weight, corresponds to the upwelling pattern, and with a negative weight corresponds to the relaxation pattern. The second EOF mode corresponds to the cyclonic pattern described here.

HW98 summarizes the near-surface circulation in the SBC in terms of synoptic views or characteristic flow patterns, initially deduced from a subjective classification of daily averages of moored current measurements, and subsequently identified with particular combinations of EOFs of the moored observations. In that representation, about 60% of variance in the observations can be categorized in terms of six flow regimes: upwelling, relaxation, cyclonic, propagating cyclones, flood east, and flood west. The three patterns described here have clear correspondence with the synoptic views presented in HW98: the upwelling, relaxation, and cyclonic patterns are the same. The cyclonic and propagating cyclonic patterns are difficult to distinguish from each other in the drifter observations, and are grouped together in this description simply as the cyclonic pattern. The upwelling and flood east patterns described in HW98 also fall into a single category in this drifter description (upwelling), as do the relaxation and flood west patterns (relaxation).

Fluctuations in the wind stress at National Data Buoy Center buoy 46054 for the 4 year period during which the releases took place are illustrated in Figure 3. The periods during which each of the 20 releases took place are also shown. There is a tendency for different patterns to occur at different times of the year. The first deployments in each year usually corresponded to the upwelling pattern. The cyclonic pattern usually occurs during the summer. In the late fall and winter the relaxation pattern is more frequently observed. HW98 suggests that the upwelling pattern occurs when the equatorward wind stress is large. This is consistent with the wind stress illustrated in Figure 3. Cyclonic patterns tend to occur when the wind stress is large and equatorward, in agreement with moored observations. Finally, the relaxation pattern takes place after the wind stress has become weaker.

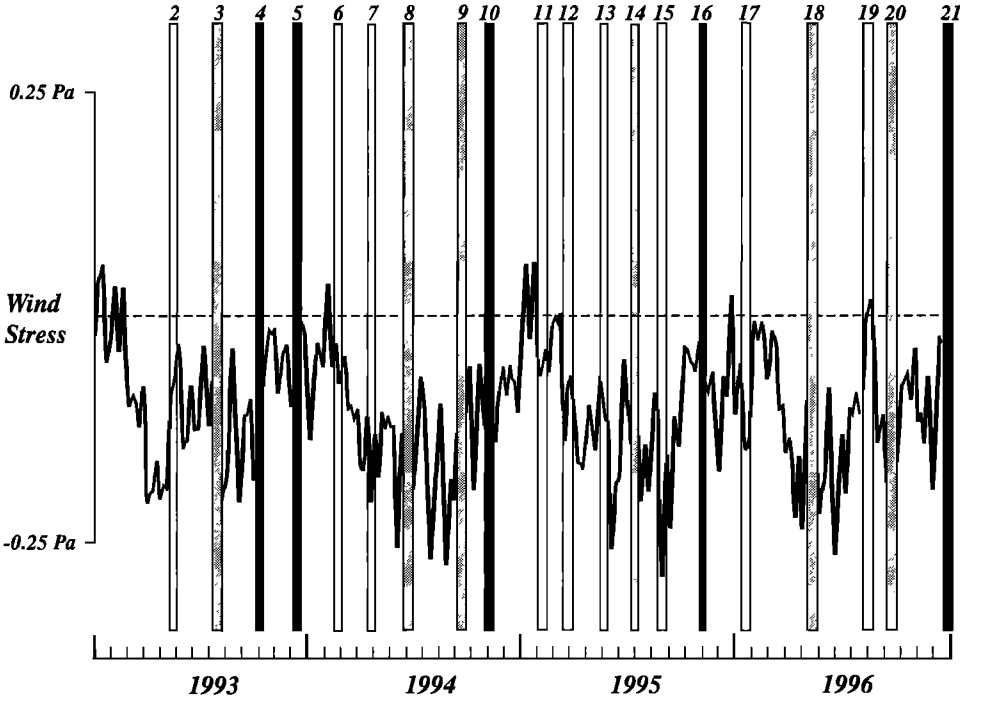

Figure 3. Low-pass filtered time series of wind stress at NDBC buoy 46054 along the major axis (122°). The sign convention is such that positive values correspond to poleward (toward the NW) stresses. The vertical bars represent 14 day periods beginning on the release date. Each bar is coded (open, shaded, solid) according to the state of circulation (upwelling, cyclonic, relaxation). The release number is noted above each bar.

3.2. Characteristic Releases

Each drifter trajectory includes circulation features which reveal interesting characteristics of the circulation but are of sufficiently small scale that they do not appear in statistical descriptions or descriptions based on moored observations. For example, there are several trajectories which exit the SBC through the passes which separate the Channel Islands. The following description of three individual releases is intended to highlight such features. AVHRR satellite images are frequently used to identify features of the surface circulation [*Lagerloef and Bernstein,* 1988] and have been compared to drifter trajectories in similar studies [e.g., *Chereskin and Niiler,* 1994; *Davis,* 1985; *Poulain and Niiler,* 1989]. Accordingly, the trajectories illustrated in this section are superimposed on maps of sea surface temperature.

3.2.1. Relaxation pattern (October 6, 1993). Equatorward winds relaxed in fall 1993, and release 4, beginning on October 6, was characterized by weak winds. Drifters were released from all sites, although the drifter released at SMIN failed to report positions. Trajectories of the individual drifters are illustrated in Figure 4.

None of the 11 drifters released left the channel through the eastern entrance, and six were carried north along the central California coast beyond Point Conception. Most of these were released in the northeast section of the channel. Once around the point, the drifters traveled north with velocities of order 0.2 m s^{-1}; three of these ran aground. Of the five remaining drifters, three went south, into the Southern California Bight, where one eventually ran aground near San Diego, and two beached, one on the south side of San Miguel Island and the other on the south side of Santa Rosa Island. Trajectories of three drifters, released at ROIN, ROMI, and GOOF, provide evidence of the cyclonic component of the circulation near the center of the channel even during this time of weak winds.

Each drifter track is superposed on the same AVHRR image, representing the average temperature over the 2 week period following the release, in an attempt to represent mean conditions for the period the drifters were in the channel. The temperature extremes in the image differ by more than 4°C. The temperature gradient is

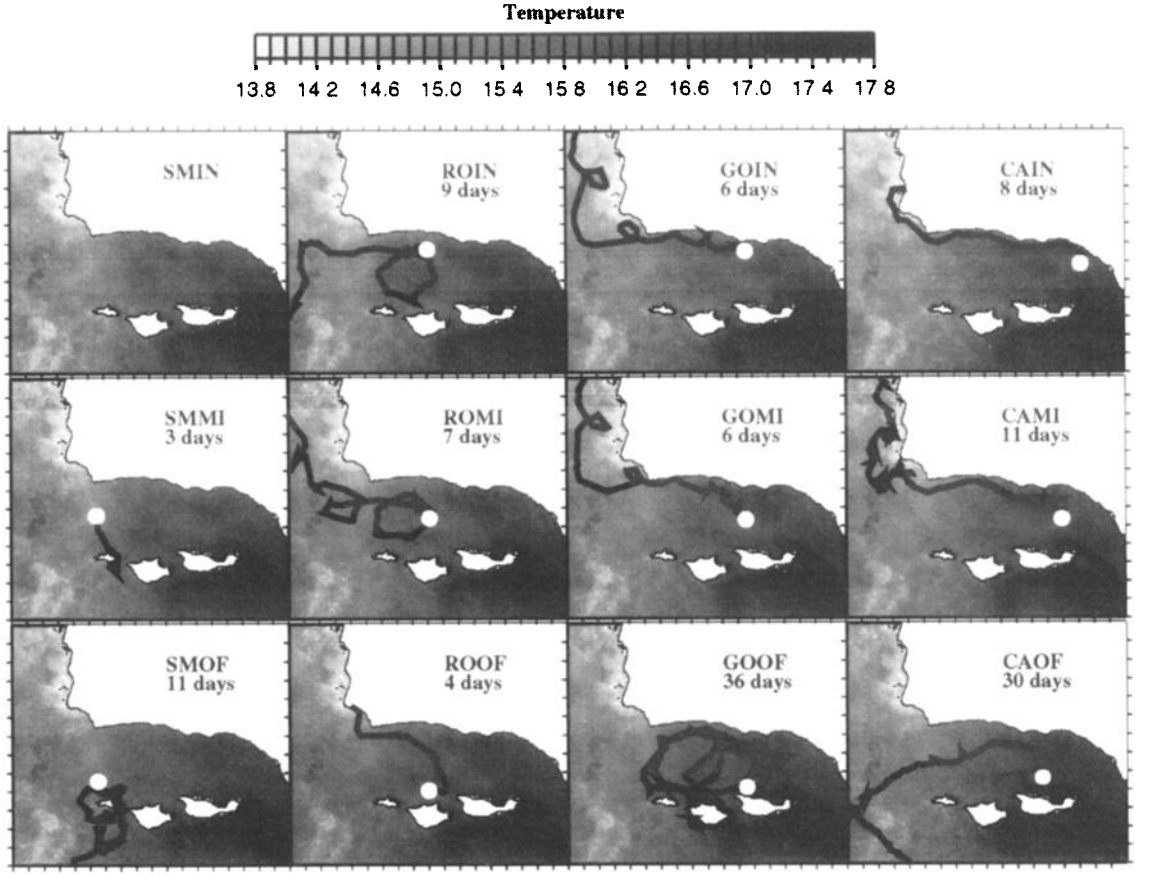

Figure 4. Individual drifter trajectories for release 4. Drifters were deployed on October 6, 1993. The drifter released at SMIN did not report positions. The time during which each drifter remained in the area illustrated in Figure 1 is noted beneath the release site. The underlying image represents average temperatures (in degrees Celsius) over the period October 6-20, 1993. The averages were computed from available AVHRR images.

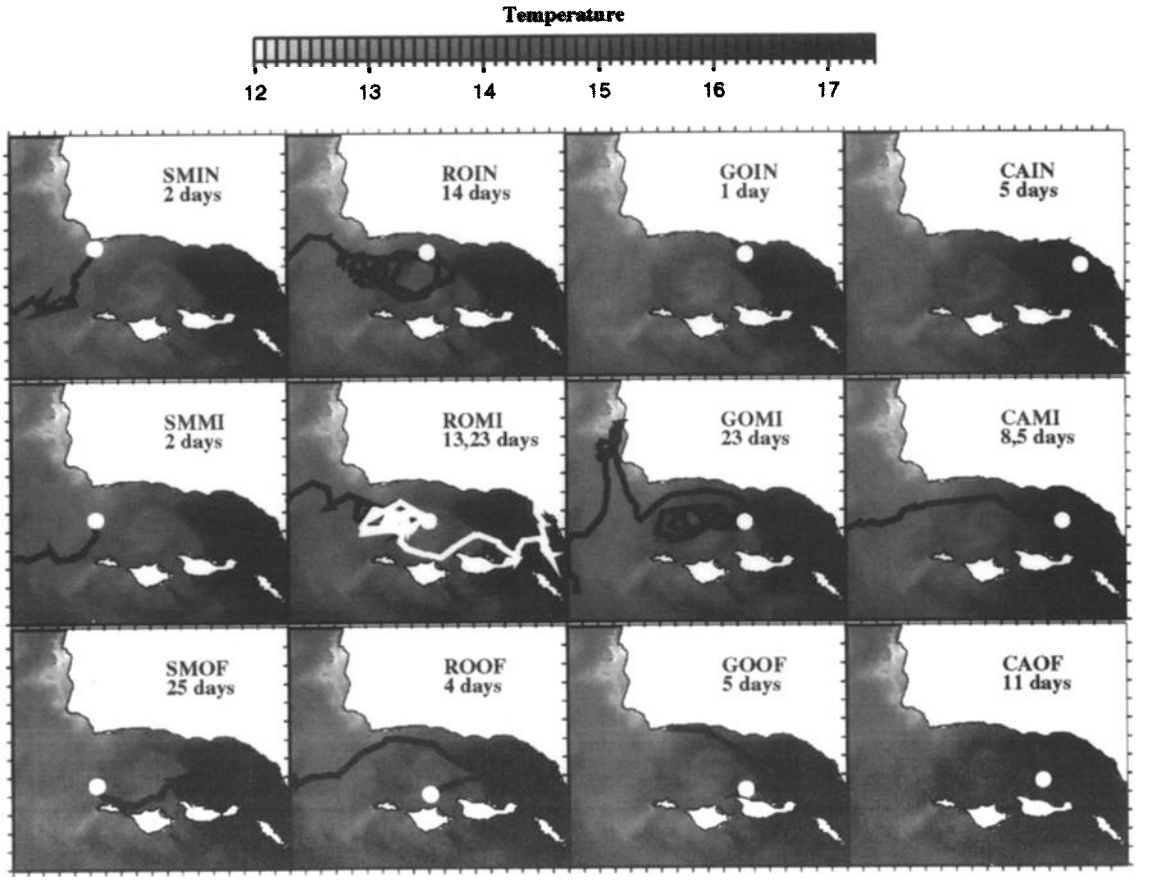

Figure 5. Individual drifter trajectories for release 9. Drifters were deployed on September 13, 1994. The time during which each drifter remained in the area illustrated in Figure 1 is noted beneath the release site. Pairs of drifters were released simultaneously at ROMI and CAMI. The underlying image represents average temperatures (in degrees Celsius) for all images received on September 14, 1994.

as expected in this area and in this season, with warmer waters in the southeastern portion of the figure. The image shows a small eddy located near the middle of the channel just above Santa Rosa island. The drifter released at ROIN appears to circle around this feature.

The variety of behaviors exhibited by drifters deployed at adjacent locations along the Channel Islands in this release demonstrates the difficulty of classifying releases in simple statistical terms. While generalities can be stated, for instance, that drifters released near the mainland coast tend to move poleward, such characterizations do not account for the rapid change in particle trajectories which can be dependent on specific release site or time of release. For example, the drifter released at ROOF crossed the channel and ran aground between Point Conception and Point Arguello soon after release; the drifter released at GOOF, 28 km east of ROOF, milled around cyclonically in the channel for 20 days accomplishing four full circuits before running aground on the south side of Santa Rosa Island; and the drifter released at CAOF, another 20 km to the east, initially moved to the north shore and then drifted westward out of the channel, then south.

3.2.2. Cyclonic pattern (September 13, 1994). An episode of strong winds favorable to upwelling ended on September 13, 1994, when the drifters in release 9 where deployed. Drifters were released at all the locations within the channel, and a pair of drifters was released at ROMI and at CAMI. This release was typical of the cyclonic circulation pattern, as several of the drifters were caught up in closed cyclonic trajectories as illustrated in Figure 5. None of the drifters left the channel through the eastern entrance.

Two of the drifters released at the western entrance (at SMIN and SMMI) initially moved toward the southwest, never entering the channel. The drifter released at SMOF, north of the San Miguel Island, initially traveled along the island chain toward the east. Having reached Santa Cruz, the drifter began milling around for several days before running aground in Chinese Harbor, on the northeastern side of the island.

The drifter released at ROIN was caught in a cyclonic gyre as soon as it was released. The drifter completed seven full revolutions with a period of about 3 days for one circuit, at the same time as it slowly drifted toward the west.

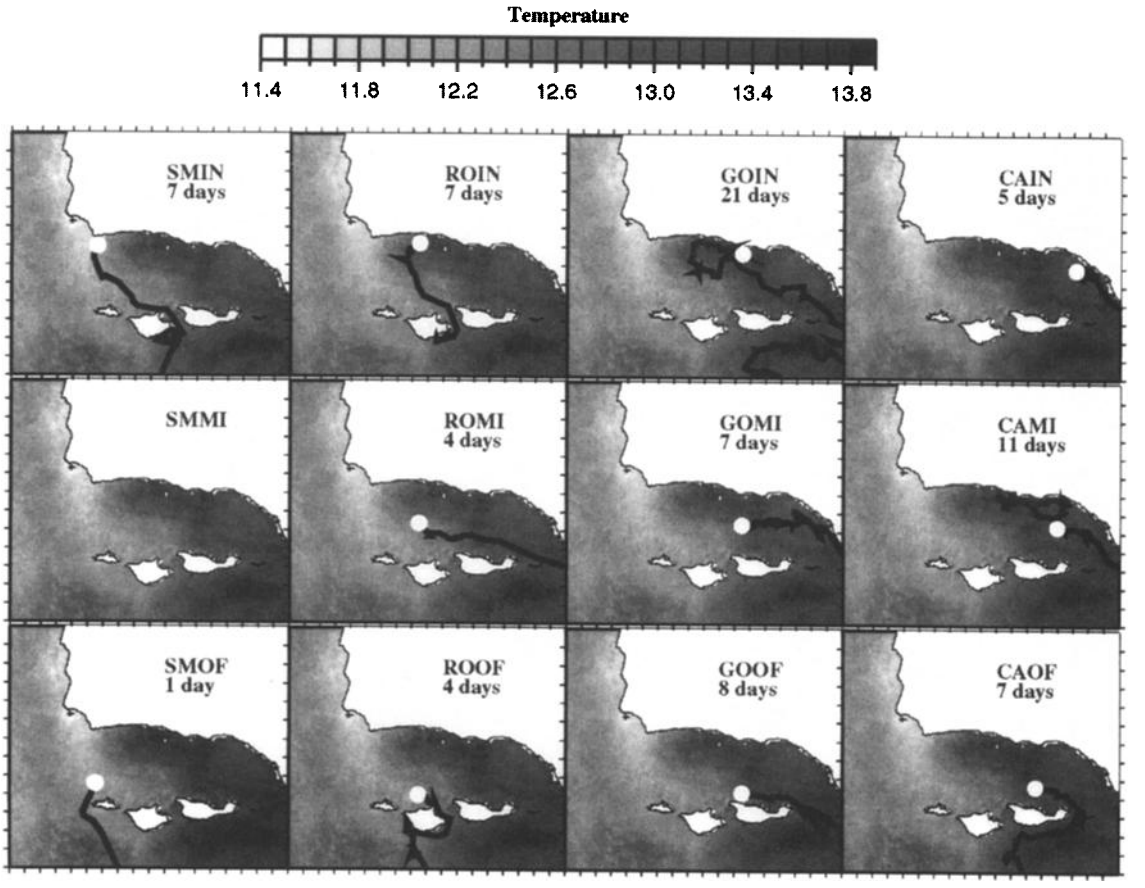

Figure 6. Individual drifter trajectories for release 12. Drifters were deployed on March 16, 1995. The drifter released at SMMI did not report positions. The time during which each drifter remained in the area illustrated in Figure 1 is noted beneath the release site. The underlying image represents average temperatures (in degrees Celsius) over the 2 week period March 16-30, 1995. The averages were computed from available AVHRR images.

Two drifters were released at ROMI, at the same time. Initially both drifters were caught up in the same cyclonic feature as the drifter released at ROIN. The radius of the revolutions of the drifters released at ROMI was smaller than for the drifter released at ROIN, suggesting that the center of the cyclonic feature was closer to ROMI. After approximately 5 days the two drifters deployed at ROMI separated. One continued to follow the drifter released at ROIN and left the channel through the western entrance. The other drifter crossed the channel to the south where it became part of the eastward current and drifted all the way to the eastern entrance. It then reversed direction, crossed the channel to the north and ran aground on the mainland coast. The behavior of this drifter pair is one of the most conspicuous examples of dispersion associated with the shear across the Santa Barbara Channel.

The drifter released at ROOF started toward the northeast. Once beyond the middle of the channel, it reversed course and left the channel at the western entrance following a similar course to the ROIN drifter and one of the ROMI drifters.

The drifter released at GOIN initially traveled toward the northwest and ran aground within 1 day of its release. The drifter released at GOMI was caught in the same gyre as drifters released in the vicinity. After five revolutions, when its position was very close to its deployment point, the drifter moved north, then west. Upon reaching the longitude of Point Conception, the drifter moved to the north, milled around for several days between Point Arguello and Point Sal, and then was caught in the general southward flowing current. The drifter released at GOOF initially traveled eastward, then reversed course, crossed the channel, and beached near Point Conception.

The drifter released at CAIN initially followed the coast poleward, and then ran aground approximately 5 days later near Santa Barbara. Two drifters were released at CAMI; both initially moved to the west, staying close together until reaching the western entrance of the channel. At this point, one turned south and the other continued toward the west, and then accomplished a broad cyclonic turn (not shown in Figure 5) at the end of which its trajectory fell in with those of other

drifters which left the channel. Finally, the drifter deployed at CAOF remained in the vicinity of the eastern tip of Santa Cruz Island until it ran aground.

Two weeklong averages of the SST mask the presence of the cyclonic feature represented in the middle of each frame in Figure 5, presumably because this feature travels sufficiently far during this period that its identity is smeared by the averaging process. Accordingly, the underlying image represents the average SST determined from images available for a single day, September 14, 1994. In this feature a cyclonic swirl of cold water is located north of Santa Rosa Island. A warm filament coming from the northern shelf is wrapped around the western and southern side of this eddy. The 5°C difference between highest and lowest temperatures on the map is characteristic for the late summer.

Of the 14 drifters released, six ran aground and eight exited through the western entrance. Those which left drifted south, with several reaching Mexican waters before the end of transmission (40 days after deployment).

3.2.3. Upwelling pattern (March 16, 1995). Release 12 occurred at the beginning of the 1995 season for winds favorable to upwelling. Trajectories are illustrated in Figure 6. Drifters released in the southwestern part of the channel drifted into the Southern California Bight between Santa Rosa and Santa Cruz Islands. The remaining drifters left the channel through the eastern entrance, between Anacapa and the mainland coast.

Drifters released along the northern shelf, at GOIN, ROIN, and CAIN, first migrated westward and toward the center of the channel, in the opposite direction from the wind. After a day the westernmost of these veered toward the southeast, joining the drifters released to the west, while the other two reversed direction and exited the channel through the eastern entrance. Several other drifters proceeded in a direct course toward the eastern exit, with speeds of order 0.2 m s^{-1}.

Three drifters left the SBC through the Santa Rosa-Santa Cruz passage. Each then first turned toward the west and followed the southern coast of Santa Cruz Island, suggesting that the flow through the passages may wrap around the islands. One drifter beached on the south shore of Santa Cruz. Two that exited from the channel's eastern end then turned to the west once they cleared the south end of Anacapa Island.

The underlying image represents a 2 week long average, beginning on the day of release. The temperature contrast across the channel is smaller than in either of the other two cases, as is expected for this period of the year. In the channel the main feature consists of a warm area near the mainland in the general vicinity of Santa Barbara. Drifters deployed at GOIN and CAMI, which initially migrated west, may have been caught in this feature before entering the generally southeast current.

3.3 Beyond the Channel

Since the lifetime of the drifters usually exceeds their residence time in the channel, the trajectories extended well beyond the SBC. Plate 1 illustrates the releases on a larger scale, superposed on average AVHRR maps for a 30 day period. When viewed from this larger perspective, trajectories also appear to fall into a few characteristic patterns.

In spring and early summer, the upwelling season, the drifters leave the SBC through the eastern exit. Once in the Southern California Bight, the trajectories occupy a broad region, a pattern usually associated with a coastal jet.

During the rest of the summer and early fall, the drifters often exit from the western entrance to the channel and drift toward the south. A remarkable feature of their subsequent trajectories is that they often remain grouped close together. In this pattern, usually associated with the cyclonic circulation in the channel, the trajectories appear to conglomerate into distinct filaments. Comparison with features of the underlying AVHRR images suggests that the filaments coincide with cooler water plumes extending south, perhaps deriving from the California current. This behavior is analogous to that exhibited by drifters during the California Coastal Transition Zone (CTZ) [*Brink et al.*, 1991].

In late fall and early winter releases, drifters exit the western entrance of the channel as they usually do in summer. However, after exiting the western channel entrance, drifter trajectories can behave quite differently than in summer. Drifters released in fall and early winter can remain over the shelf and be caught up in poleward flow to the north. This is observed in October 1993, December 1993, and December 1996. In October 1993 and December 1993, drifters remain over the shelf and flow north to approximately Point Sur, where they are carried offshore. In December 1996, drifters remain over the shelf beyond Point Sur. The majority beach in Monterey Bay; however, one drifter continued past Point Reyes before its 40 day tracking period ended, and another was later recovered off Astoria, Oregon, indicating at least the possibility of continuous poleward flow between the Santa Barbara Channel and the northern California coast in late fall and early winter.

The question naturally arises as to how these trajectories, viewed on the large scale, can be reconciled with existing descriptions of circulation in the Southern California Bight, based either on hydrographic observations [*Hickey,* 1979; *Lynn and Simpson,* 1987], or on drifter observations [*Chereskin and Niiler,* 1994; *Poulain and Niiler,* 1989]. Maps of the dynamic height referenced to 500 db consistently suggest the presence of a closed cyclonic circulation in the Southern California Bight in summer and fall. That feature is on a scale substantially larger than the cyclone which is present within the SBC. Yet of the 235 drifter releases described in this report, only one trajectory, release 15, shows evidence of a closed circulation in the Southern California Bight. This result could be due to the relatively small area over which drifters were seeded. The prevailing

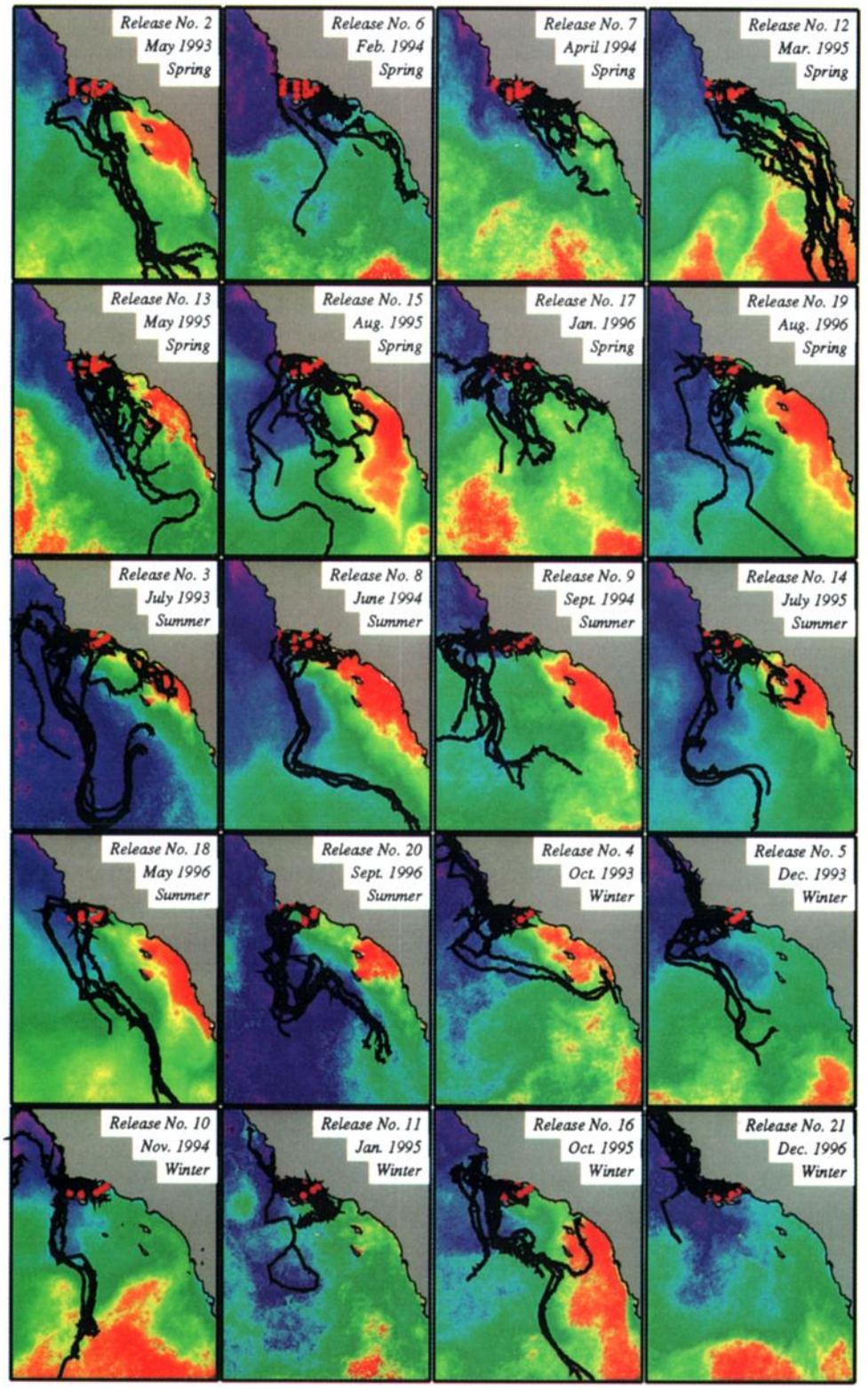

Plate 1. Comparison of drifter trajectories for individual releases on the scale of the Southern California Bight. Underlying color images represent the average temperature over the 30 day period beginning on the date of the release. The temperature scale is adjusted to maximize the contrast over each image, Warmer temperatures correspond to red-orange colors and colder temperatures correspond to blue-purple colors. Images are grouped according to the large-scale flow pattern, designated as spring, summer or winter.

pattern of surface trajectories during summer and fall is more consistent with the idea of a filament, similar to the pattern described by *Chereskin and Niiler* [1994].

4. Residence Times and Groundings

In order to describe the time period during which drifters remain in the channel, a residence time is defined as the average period for which a group of drifters remain in a region extending from 33.75°N to 34.65°N and from 120.7°W to 119.2°W. This area extends from Port Hueneme to Point Arguello and includes the south shore of the Channel Islands. The area was chosen based on the observation that once a drifter is outside these boundaries, it rarely returns.

The average residence time for all drifters which do not ground is 8 days. This time does not depend strongly on the prevailing circulation pattern: For upwelling/relaxation/cyclonic patterns the corresponding residence times are 8/7/6 days. One explanation for this result may be that all the circulation patterns include the cyclonic component. The cyclonic circulation tends to prolong residence times independent of whether the flow averaged across a section of the channel is poleward or equatorward.

The results summarized in Table 1 show that 78 of the 235 drifters (or over 30%) released in the channel ran aground, and the majority of these incidents occurred within the channel. Outside the SBC, Santa Monica Bay was a common grounding site. During the late fall and winter, groundings also occurred along the central California coast, well north of the channel. Locations of all the sites where drifters ran ashore in the SBC and vicinity are illustrated in Figure 7. The sites are distributed almost continuously along the mainland coast within the SBC, as well as along the north facing coast of the Channel Islands. A few drifters ran aground on the south side of the Channel Islands. Chinese Harbor, on the north side of Santa Cruz Island, appears to be a site where drifters run aground more often.

In view of the cyclonic circulation in the SBC, it might be expected that drifters released at different sites would run aground in specific areas of the channel. The location where drifters ran aground is illustrated in Figure 8 for each release site. Drifters launched from the northern end of the line between Point Conception and San Miguel (SMIN and SMMI) had the shortest residence times and were the least likely to ground. Times until grounding were also quite short. No drifters launched from these sites grounded on the mainland coast east of the launch point. The Channel Islands were generally favored as grounding points. For drifters launched on the SM line, groundings on San Miguel occurred for all synoptic conditions, while groundings on Santa Rosa and Santa Cruz occurred for upwelling and cyclonic conditions.

Drifters launched along the RO line extending north from Santa Rosa also tended to ground along the Channel Islands, generally during upwelling or cyclonic conditions. The exception is San Miguel Island, which had

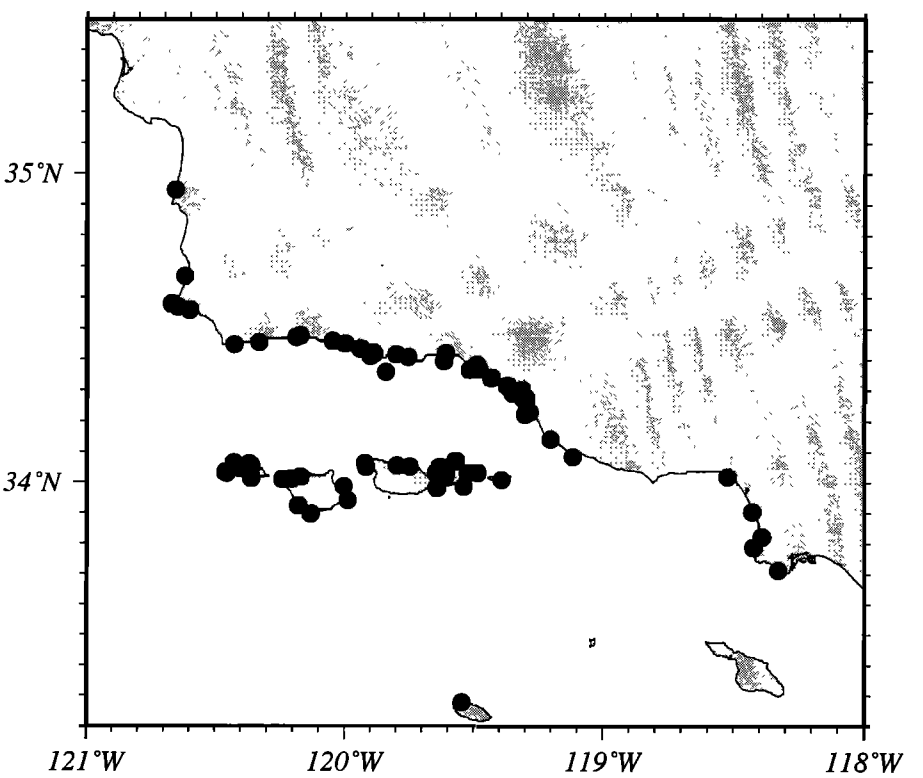

Figure 7. Location where drifters released in the course of this experiment ran aground.

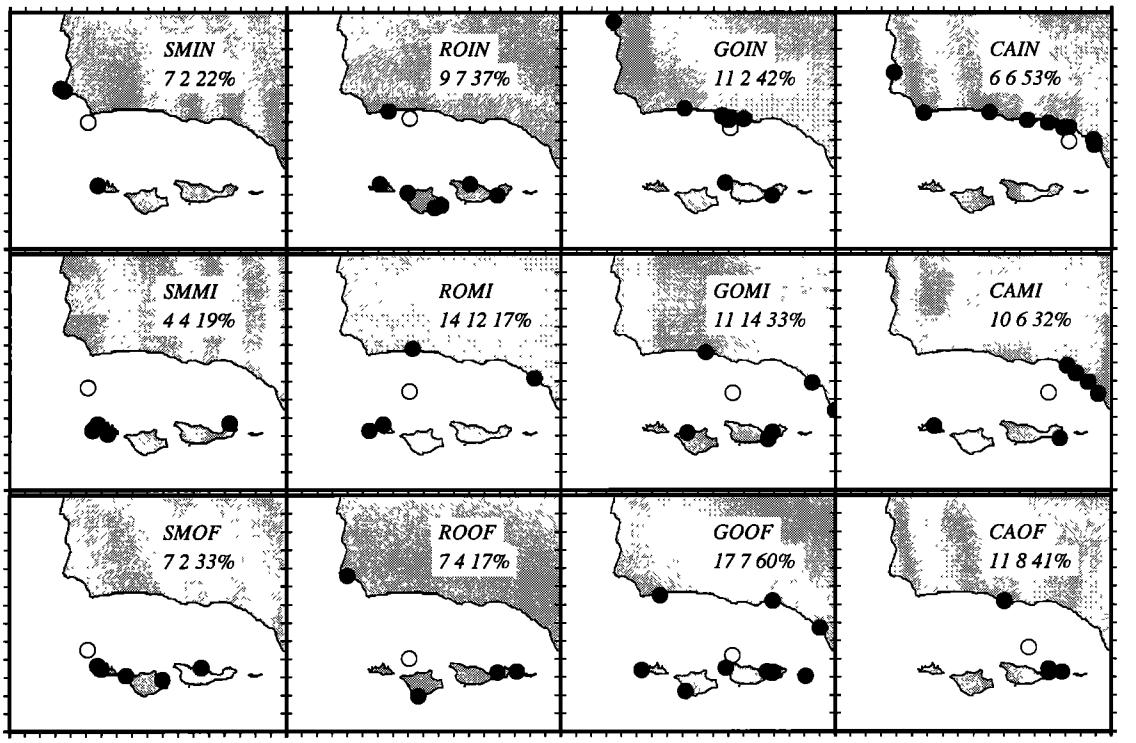

Figure 8. Location where drifters released in the course of this experiment ran aground, segregated by the position of release. The release position is shown by the open circle. The first inset number represents the median residence time for all drifters launched from each site (in days). The second number represents the median time (in days) before drifters that beach run aground. The third number is the percentage of all drifters launched at each site which ran aground.

several drifters ground on it during relaxation conditions as well.

Drifters launched along the GO line extending north from Santa Cruz often beached along the mainland as well as the Channel Islands. Drifters launched at GOIN were particularly likely to beach along the mainland coast near their launch point for the upwelling state. Drifters launched at GOMI also occasionally beached on the mainland coast between Santa Barbara and Port Hueneme during upwelling conditions. Drifters launched at GOOF had the highest likelihood of grounding of all deployment locations. Under cyclonic or upwelling conditions the beaching point was often at Chinese Harbor on Santa Cruz. Drifters which beached on either the mainland or Channel Island coasts west of the GO line did so under cyclonic or relaxation conditions.

Drifters launched along the CA line generally beached east of their launch point under upwelling or cyclonic conditions. The few which beached west did so under cyclonic or relaxation conditions. Drifters launched at CAIN and CAMI tended to ground over the relatively broad shelf extending between Santa Barbara and Port Hueneme (Figure 1). These groundings generally occurred under upwelling or cyclonic conditions. Drifters launched at CAOF often grounded on Santa Cruz under cyclonic or upwelling conditions.

Drifters launched in the northwestern SBC where the persistent cyclonic circulation keeps the velocity high tend to exit the channel rapidly and are the least likely to beach. Conversely, drifters launched north of Santa Cruz where average speeds are slower remain in the channel longer and are more likely to beach. Cross-channel exchange of drifters is generally highest in the western Santa Barbara Channel, with several of the drifters launched at SMIN and ROIN beaching on the Channel Islands. In the eastern channel, many drifter release locations (GOIN, GOOF, CAIN, CAMI, and CAOF) favor beaching relatively near the release location.

5. Summary

The central result of this description is to document the existence of a persistent cyclonic circulation in the SBC. Beyond this ubiquitous feature, the circulation can usually be described in terms of three possible patterns. In the upwelling pattern, drifters exit the channel within a few days, either through the passages which separate the Channel Islands, or more frequently through the eastern entrance between Anacapa Island and Port Hueneme. In the cyclonic pattern, drifters tend to remain in the SBC for more than a week, particularly those which have been released away from the

entrances. Drifters describe anticlockwise trajectories with a period of 3 to 5 days. HW98 has shown how in some cases these cyclones propagate toward the east, with in one instance a velocity of 0.06 m s^{-1}. After only a short residence time in the channel, drifters released during relaxation patterns migrate out of the channel through the western entrance, between Point Conception and San Miguel Island. Subsequently, many of the drifters (and most of those released along the northern side of the channel) migrate poleward along the central California coast.

These three patterns tend to occur at different times of the year. The upwelling pattern usually occurs in the early spring, after winds become persistently equatorward. The cyclonic pattern appears most frequently during the late spring, the summer, and early fall, when winds are still persistent and equatorward and when the sea level difference is in a direction opposite to the wind stress. Finally the relaxation pattern usually occurs in late fall and through the winter, when the winds are no longer persistently equatorward, but the sea level remains higher to the south.

It is significant for oil spill risk analysis that about one third of the 235 drifters released in this study ran ashore, for the most part in the SBC, either along the mainland coast or on the Channel Islands. Drifters released on the northern side of the western entrance had the least likelihood of beaching, presumably because of the persistent westward current in this area, which tends to sweep the drifters offshore, where they become entrained into the California current system.

Drifters released at CAIN and GOOF were the most likely to run aground. Over half the drifters released at CAIN beached along the mainland California coast, to the west of their release site. It is noteworthy that this location is close to the site of the oil spill which occurred in 1969 and resulted in extensive oiling of beaches and coastal areas in the channel. Drifters released from GOOF tended to beach along the Channel Islands, with multiple groundings in Chinese Harbor, on Santa Cruz Island. Sites from which a large number of drifters ran aground are sites where the average current is weak.

Beyond the Santa Barbara Channel, drifters take a variety of paths. Drifters launched in spring tend to exit the eastern entrance of the channel and continue south into the Southern California Bight. In summer, drifters tend to exit the western entrance to the channel and be carried south in patterns analogous to those deployed in the Coastal Transition Zone (CTZ) study. Drifters launched in fall and early winter exit the western entrance to the Santa Barbara Channel. After exiting, they can remain on the shelf and move poleward for periods of weeks. Offshore flow can occur near Point Sur, or drifters may continue flowing poleward into Monterey Bay and on to the northern California coast.

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References

Atkinson, L. P., K. H. Brink, R. E. Davis, B. H. Jones, T. Paluszkiewicz, and D. W. Stuart, Mesoscale hydrographic variability in the vicinity of Point Conception and Arguello during April-May 1983: The OPUS 1983 Experiment, *J. Geophys. Res., 91*(C11), 12,899-12,918, 1986.

Barth, J. A., and K. H. Brink, Shipboard Acoustic Doppler Profiler velocity observations near Point Conception: Spring 1983, *J. Geophys. Res., 92*(C4), 3925-3943, 1987.

Brink, K. H., The near-surface dynamics of coastal upwelling, *Prog. Oceanogr., 12*, 223-257, 1983.

Brink, K. H., and R. D. Muench, Circulation in the Point Conception-Santa Barbara Channel region, *J. Geophys. Res., 91*(C1), 877-895, 1986.

Brink, K. H., D. W. Stuart, and J. C. Van Leer, Observations of the coastal upwelling region near 34° 30'N off California: Spring 1981, *J. Phys. Oceanogr., 14*, 378-391, 1984.

Brink, K. H., R. C. Beardsley, P. P. Niiler, M. Abbott, A. Huyer, S. Ramp, T. Stanton, and D. Stuart, Statistical properties of near-surface flow in the California coastal transition zone, *J. Geophys. Res., 96*(C1), 14,693-14,706, 1991.

Caldwell, P. C., D. W. Stuart, and K. H. Brink, Mesoscale wind variability near Point Conception, California during spring 1983, *J. Clim. Appl. Meteorol., 25*, 1241-1254, 1986.

Chelton, D. B., Seasonal variability of alongshore geostrophic velocity off central California, *J. Geophys. Res., 89*(C3), 3473-3486, 1984.

Chereskin, T. K., and P. P. Niiler, Circulation in the Ensenada front-September 1988, *Deep Sea Res. II, 41*(8), 1251-1287, 1994.

Davis, R. E., Drifter observations of coastal surface currents during CODE: The method and descriptive view, *J. Geophys. Res., 90*(C3), 4741-4755, 1985.

Dever, E.P., M.C. Hendershott, and C.D. Winant, Statistical aspects of surface drifter observations of circulation in the Santa Barbara Channel, *J. Geophys. Res., 103*(C11), 24,781-24,797, 1998.

Dorman, C. E., and C. D. Winant, Buoy observations of the atmosphere along the west coast of the U.S., 1981-1990, *J. Geophys. Res., 100*(C8), 16,029-16,044, 1995.

Dorman, C. E., and C. D. Winant, The marine layer in and around the Santa Barbara Channel, *Mon. Weather Rev.*, in press, 1999.

Gunn, J. T., P. Hamilton, H. J. Herring, K. L. Kantha, G. S. Lagerloef, G. L. Mellor, R. D. Muench, and G. R. Stegen, Santa Barbara Channel circulation model and field study, final report, *Dynalisis Princeton, Rep. 92.1, 92.2*, Princeton, N.J., 1987.

Harms, S., and C. D. Winant, Characteristic patterns of the circulation in the Santa Barbara Channel, *J. Geophys. Res., 103*(C2), 3041-3065, 1998.

Hendershott, M. C., and C. D.Winant, The circulation in the Santa Barbara Channel, *Oceanography, 9*(2), 114-121, 1996.

Hickey, B. M., The California current system-Hypotheses and facts, *Prog. Oceanogr., 8*, 191-279, 1979.

Hickey, B. M., Circulation over the Santa Monica-San Pedro basin and shelf, *Prog. Oceanogr.*, *30*, 37-115, 1992.

Huyer, A., Coastal upwelling in the California current system, *Prog. Oceanogr.*, *12*, 259-284, 1983.

Kolpack, R. J., *Biological and Oceanographical Survey in the Santa Barbara Channel Oil Spill 1969-1970*, vol. 2, chap. 4, pp. 90-180, Allan Hanock Foundation, Univ. of Southern Calif., 1971.

Lagerloef, G. S., and R. L. Bernstein, Empirical orthogonal function analysis of advanced very high resolution radiometer surface temperature patterns in the Santa Barbara Channel, *J. Geophys. Res.*, *93*(C6), 6863-6873, 1988.

Lentz, S. J., and C. D. Winant, Subinertial currents on the southern California shelf, *J. Phys. Oceanogr.*, *16*, 1737-1750, 1986.

Lynn, R. J., and J. J. Simpson, The California current system: The seasonal variability of its physical characteristics, *J. Geophys. Res.*, *92*(C12), 12,947-12,966, 1987.

Poulain, P.-M., and P. P. Niiler, Statistical analysis of the surface circulation in the California current system using satellite-tracked drifters, *J. Phys. Oceanogr.*, *19*, 1588-1603, 1989.

Winant, C. D., and C. E. Dorman, Seasonal patterns of surface wind stress and heat flux over the Southern California Bight, *J. Geophys. Res.*, *102*(C3), 5641-5653, 1997.

Winant, C. D., R. C. Beardsley, and R. E. Davis, Moored wind, temperature, and current observations made during Coastal Ocean Dynamics Experiments 1 and 2 over the northern California continental shelf and upper slope, *J. Geophys. Res.*, *92*(C2), 1569-1604, 1987.

D. J. Alden, E. P. Dever, K. A. Edwards, M. C. Hendershott, and C. D. Winant, Center for Coastal Studies, Scripps Institution of Oceanography, University of California at San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0209. (email: dja@coast.ucsd.edu; dever@coast.ucsd.edu; kate@coast.ucsd.edu; mch@coast.ucsd.edu; cdw@ucsd.edu)

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