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The circulation and water masses in the Gulf of the Farallones

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Abstract

Six ADCP and CTD ship surveys of the continental shelf and slope in the vicinity of the Gulf of the Farallones, CA, were conducted in 1990–1992. ADCP data provide much more detail on the structure of the currents over the slope and shelf in the Gulf and reveal a persistent, largely barotropic poleward flow with a complex mesoscale flow field superimposed. The directly measured currents are not well represented by the geostrophic velocity fields derived from hydrographic casts. Important upper-ocean circulation features include: a Slope Countercurrent (SCC), variable shelf circulation, and submesoscale eddy-like features. The SCC was present in all seasons and is believed due to a strong year-round positive wind-stress curl enhanced by Point Reyes. Its flow was poleward throughout the upper 300 m, and often surface intensified. Poleward transport in the upper 400 m was 1–3 Sv, much greater than previous geostrophic estimates for the California Current System constrained to a 500 dbar reference level. The shelf circulation was much more variable than the SCC and generally exhibited a pattern consistent with classic Ekman dynamics, responding to synoptic wind forcing. Submesoscale vortices, or eddies, often dominated the general flow field. These eddies are thought to be generated by the frictional torque associated with current–topography interactions. Their centers typically have a distinct water type associated with either the SCC or the southward-flowing California Current. Higher spiciness anomalies, representing a higher percentage of Pacific Equatorial

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Water (PEW), were typically found in the core of the SCC or within anticyclonic eddies. Lower (bland) spiciness anomalies, characteristic of a higher percentage of Pacific Subarctic Water (PSAW), were associated with cyclonic eddies. While these circulation features were largely barotropic, the flow also adjusted baroclinically to changes in the density field, as different water types were advected by the general flow field or by mesoscale instabilities in the large-scale boundary currents as they interacted with topography. Despite a seasonal cycle in regional wind and ocean temperature time series, there is no obvious seasonal pattern in the circulation. Most of the temporal variability in the current appears to be due to synoptic and interannual variations in atmospheric forcing. Because of the very dynamic three-dimensional nature of the regional circulation, the Gulf of the Farallones is likely to be a center for active mixing and exchange between the coastal and California Current waters, relative to most US west coast locales.

1. Introduction

Although well traversed, the Gulf of the Farallones (Fig. 1), entry to San Francisco Bay, has received little scientific investigation. South of the Gulf, Monterey Bay has been studied for decades. Similarly, a number of large experiments have been conducted north of the Gulf in the last two decades, including the Coastal Ocean Dynamics Experiment (CODE), Northern California Coastal Circulation Study (NCCCS), and Coastal Transition Zone (CTZ) programs. A few cruises and current meter deployments have provided limited insight on the Gulf's circulation and structure.

The Gulf of the Farallones region is unique in several ways. The coastline features numerous indentations and headlands. Point Reyes, the most prominent, shelters the Gulf from the predominantly northwesterly winds and may deflect or disrupt coastal winds and the alongshore current. Fresh water from San Francisco Bay enters the Gulf through the Golden Gate. The continental shelf from Oregon to Point Conception is typically about 20 km wide; however, it widens to almost 50 km within the Gulf. The Farallon Islands lie near the steep continental slope, which is broken by several canyons and seamounts and reaches 3000 m depth within 20–50 km of the shelf break.

In terms of the seasonal circulation, Lynn and Simpson (1987) found that flow in the Gulf of the Farallones is poleward in winter and equatorward in summer. Largier et al. (1993) characterized the region north of Point Reyes in terms of three seasons: upwelling (April–July), relaxation (August–November), and storm (December–March). During the relaxation season, a poleward pressure gradient counters the upwelling-favorable wind stress, producing a poleward near-surface flow during periods of weak equatorward stress. Irrespective of season, the near-surface flow was predominantly equatorward and reached a minimum south of Cape Mendocino, where it was associated with a maximum in the poleward undercurrent.

In contrast, Hickey and Pola (1983) describe a poleward pressure gradient in all months but January and February, reaching a maximum in late summer. Variations in the California Undercurrent are consistent with this. Current-meter time series

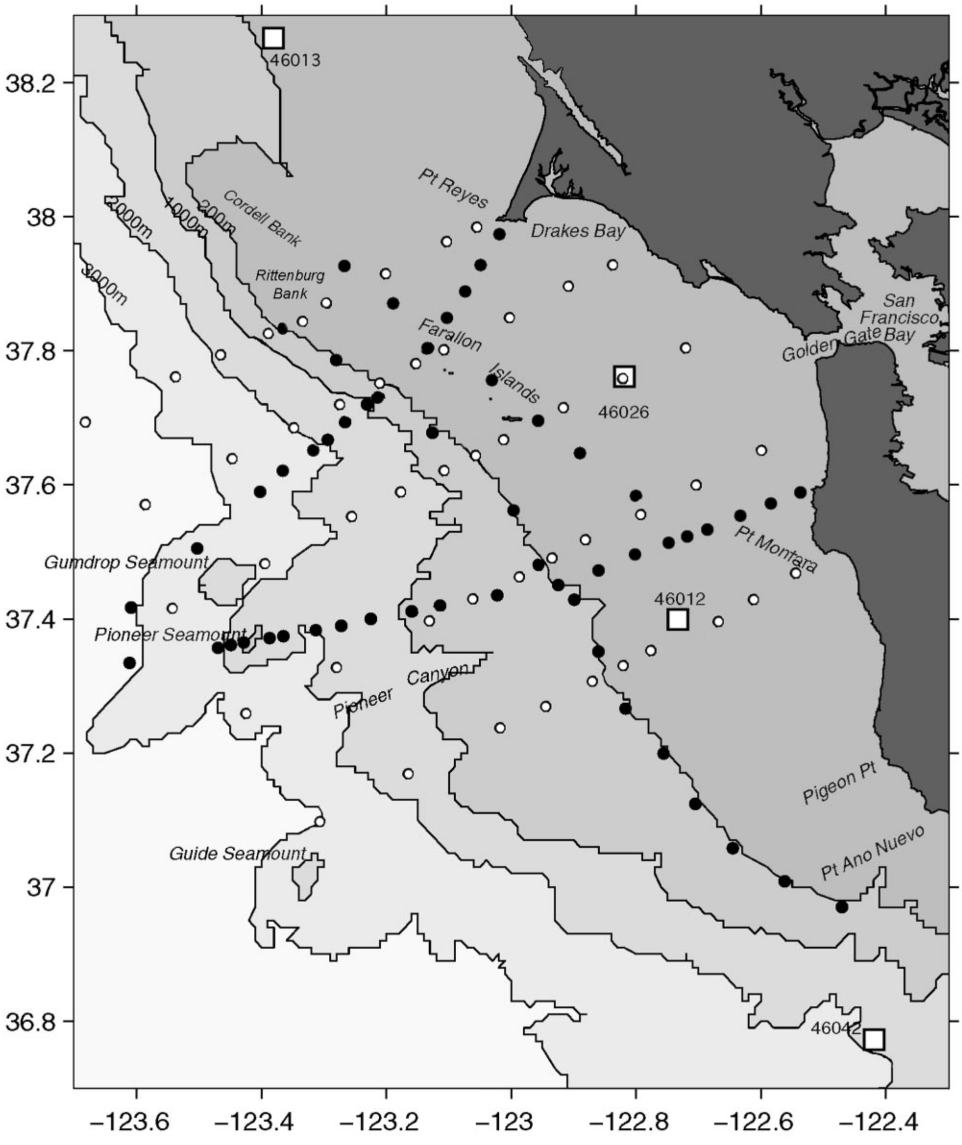


Fig. 1. The Gulf of the Farallones. Locations of CTD stations for the slope/shelf Experiment are marked with open circles. Closed circles denote August 1990 CTD stations. National Data Buoy Center buoy mooring locations are indicated by open squares. Bathymetry zones 0–200, −1000, −2000, −3000 and > 3000 m have gradually decreasing shading.

(March 1991–February 1992) from this study show persistent, often surface intensified, poleward currents over the slope (Noble and Ramp, 2000).

A major limitation in our ability to describe the interaction between eastern boundary current and coastal waters has been a general lack of horizontal spatial resolution over the shelf and offshore regions. For example, hydrographic station spacing in the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program is typically 40 km or more (cf. Lynn et al., 1982), much too large to capture the true complexity of the California Current and coastal waters. Satellite images, in contrast, suggest a circulation pattern featuring 10–50 km diameter vortices not seen in large-scale surveys (Rosenfeld et al., 1994).

Are poleward currents in this region a seasonal phenomena as Largier et al. (1993) have suggested, or a year-around feature as Noble and Ramp (2000) found? Are there dynamic submesoscale features in the Gulf of the Farallones, as suggested by AVHRR imagery, that are not detected in historical in situ data set? This study provided an opportunity to examine the interaction between submesoscale shelf/slope processes and the California Current, which represents a potentially significant mechanism for the exchange of material between the coastal and deep ocean. It also lends insight to the role of a complex coastline and bathymetry on the nature of coastal circulation. The focus of this paper is to describe the Gulf's circulation and suggest what mechanisms may be responsible for this pattern and its variability. Vessel-mounted Acoustic Doppler Current Profiler (ADCP) and CTD cast data from six brief surveys in all seasons are the principal data sets analyzed here. Supporting data from meteorological observations are examined as well.

2. The slope/shelf experiment cruises

To enhance our understanding of the circulation in the Gulf of the Farallones region, a 13-month field program was sponsored by the Environmental Protection Agency and the Naval Facilities Engineering Command, Western Division. Five cruises — February, May, August, and October/November 1991 and February 1992 — were made to determine the likely dispersal pattern of dredge spoils proposed to be deposited periodically in the area (Ramp et al., 1995). An additional, exploratory cruise was conducted in August 1990 (Gezgin, 1991).

CTD casts were made along five cross-shelf lines, 20 km apart, that covered the Gulf from Pigeon Point to Point Reyes and seaward to the 3000 m isobath (Fig. 1). Cross-shelf station spacing was 5–10 km, with closer spacing over the continental slope. The grid was occupied once each cruise, except that the northernmost line was missed in February 1992. Spiciness anomalies were calculated from CTD data using the methods and reference levels of Flament (1986). Density anomalies were computed using the Matlab© SEAWATER package (Morgan, 1994). Geostrophic calculations were computed from individual CTD casts. In depths less than 500 m these were made by extending the deeper isopycnals inshore horizontally, per Reid and Mantyla (1976).

Water velocity data were collected continuously throughout each cruise with a 150–kHz vessel-mounted Acoustic Doppler Current Profiler (ADCP), during the CTD survey and a subsequent non-stop ADCP survey. Data were saved in 8-m depth bins from 15 m to generally 400 + m, depending on sea conditions and bottom depth. Details on the processing and summaries of CTD and ADCP data are available in a series of data reports (Jessen et al., 1992a,b,c,d; Rago et al., 1992). Tidal velocities for each ADCP data bin were estimated with an empirical tidal model of the Gulf (Steger, 1997; Steger et al., 1998), and then subtracted from the ADCP data.

ADCP and CTD data were gridded horizontally and vertically for contouring and transport calculations. Values at each gridpoint were calculated by finding all data within a radial horizontal distance of the gridpoint ($1/10^{\circ}$ for horizontal grids, 8 km for vertical transections) and calculating a distance-weighted average. Alongshore-averaged vertical transects were made using the distance of each ADCP ensemble from the 200-m isobath, the approximate location of the shelf break, as the cross-shelf coordinate system.

AVHRR satellite imagery was sufficiently cloud-free to detect sea-surface temperature (SST) features in the region during four of the five cruises. The data are channel 4 radiance values that have not been corrected for atmospheric path length contamination. Therefore relative, not absolute, SST values are shown.

3. Regional WIND/SST climatology and conditions in 1991–92

Daily averaged alongshore winds and SST at four nearby NOAA National Data Buoy Center (NDBC) buoys from January 1991 to March 1992 are shown in Figs. 2 and 3, respectively (buoy locations are shown in Fig. 1). Within the generally spatially coherent wind field are submesoscale differences that reflect potentially important variations in coastal ocean forcing. Winds at the Bodega Bay buoy were generally stronger and directed clockwise relative to buoys to the south, while the Farallones buoy winds were weaker and directed more eastward than winds at adjacent buoys. Wind speeds north of Point Reyes and seaward of the Gulf are historically stronger than those in the Gulf (Nelson, 1977). Overall, the region's winds appear to feature a persistent positive curl.

On seasonal scales, winds in 1991 and early 1992 were not particularly unique. However, winds prior to and during individual surveys deviate greatly from the seasonal cycle, and reflect the high synoptic-scale variability typical of this region. The latter part of the February 1991 cruise experienced substantially stronger than normal equatorward winds, while the May and October surveys began with stronger than average equatorward winds that relaxed during the cruise. The August cruise began a day after a short period of anomalously poleward winds, but took place during relatively average (weak equatorward) winds. Sustained strong poleward winds occurred throughout the February 1992 survey. It will be shown that ocean circulation and structure appear linked to the recent local wind conditions in all five cruises.

SSTs were unseasonably low throughout January–June 1991, then near-normal until the end of January 1992 (Fig. 3). At that point, SST became anomalously warm,

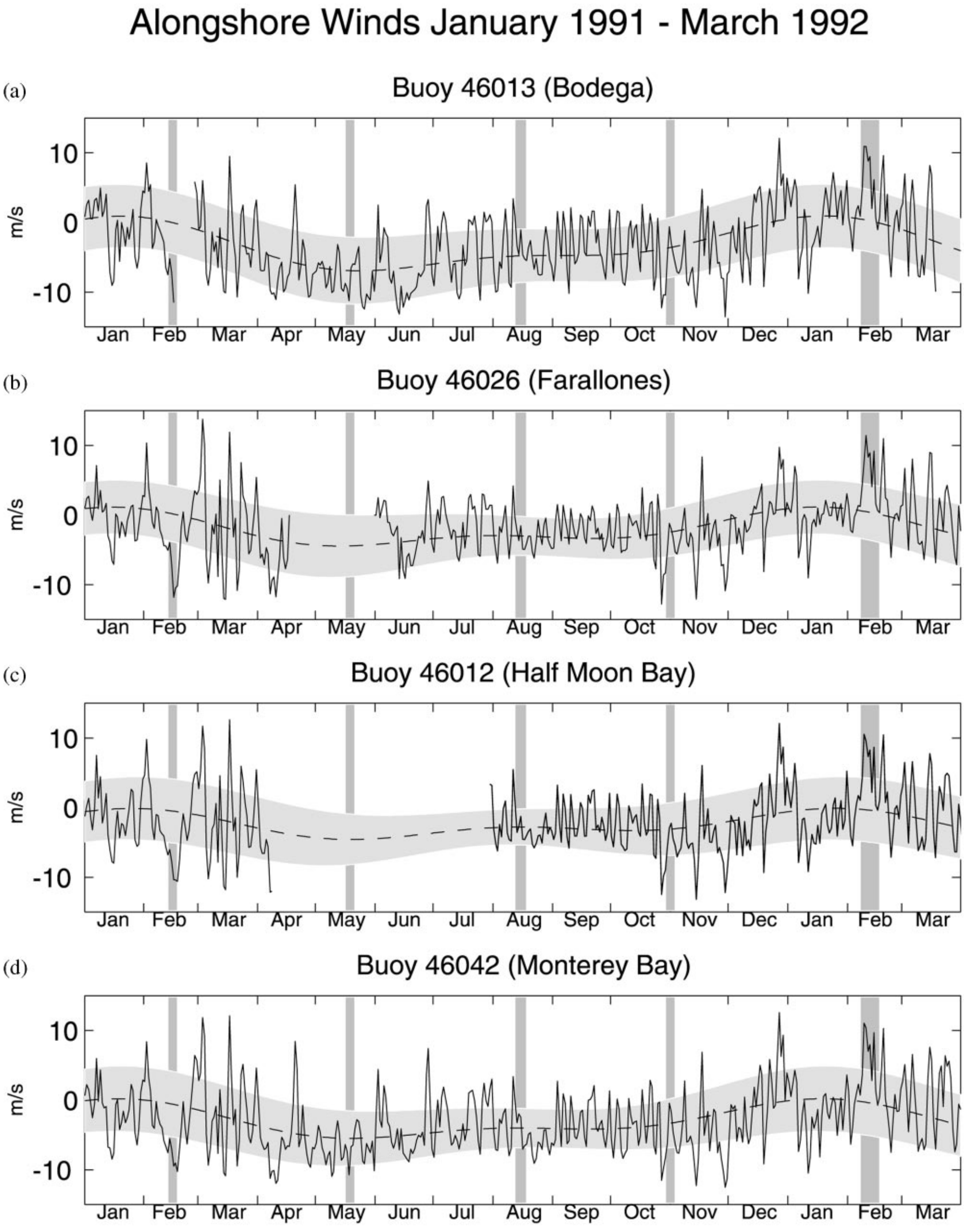


Fig. 2. Alongshore winds at NDBC buoys (a) 46013, (b) 46026, (c) 46012, and (d) 46042 between January 1991 and March 1992. Dark line is daily winds. The dashed line is a biharmonic (annual and semiannual) fit to daily winds from 1991–1996. Daily standard errors were calculated for each julian day, then fit to a biharmonic curve. The envelope between ± 1 standard error is shaded. Cruise periods are also indicated by vertical bands of shading. The direction of the alongshore component at each buoy relative to true north, determined from principal component analysis, is 132° (46013), 128° (46026), 152° (46012), and 148° (46042).

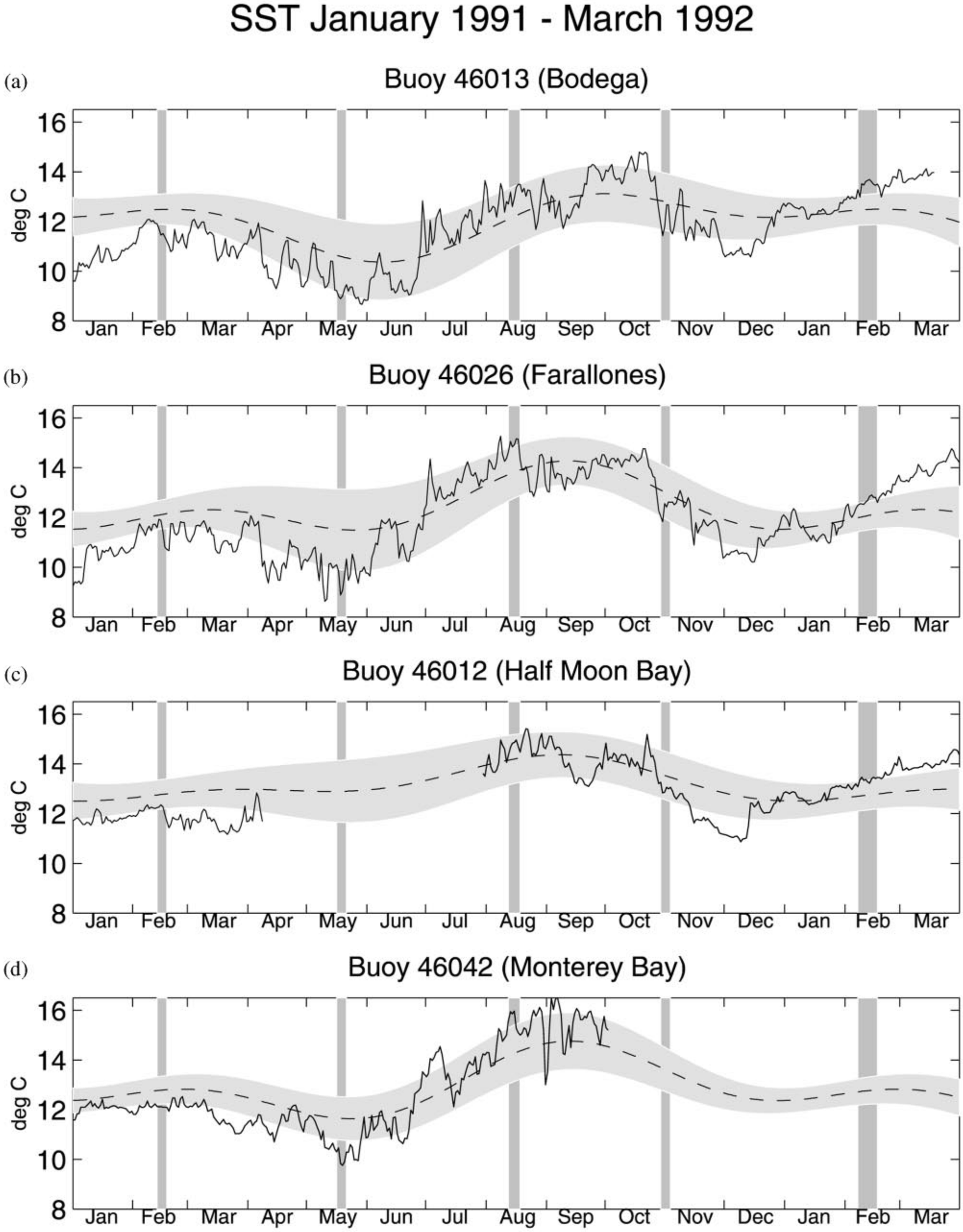


Fig. 3. Sea surface temperature (SST) at NDBC buoys (a) 46013, (b) 46026, (c) 46012, and (d) 46042 between January 1991 and March 1992. Same as for Fig. 2, but for SST.

lagging by about one month the arrival of the initial warm signal of the 1992–93 El Niño in the eastern equatorial Pacific. Synoptic-scale events resulted in cooler than normal SSTs during the February, May and October 1991 surveys, and warmer SSTs through the August 1991 and February 1992 cruises. A comparison of winds in each year suggests the local meteorological signal was not greatly affected by this tropical El Niño. Thus interannual temperature differences were probably associated with some remote component of El Niño (Lynn et al., 1995; Ramp et al., 1997).

4. ADCP and CTD fields

Horizontal velocity plots for 20 m (averaged over 15–23 m depth bins) and 100 m (averaged over 95–103 m depth bins) and an alongshore-averaged vertical section of velocity are presented for each cruise from the 1991–1992 program. Conditions at 20 m are representative of the near-surface, and for clarity will be referred to as such in this section. The 100-m fields represent conditions within the pycnocline. Spiciness anomalies are shown for each survey on isopycnal surfaces (25.5 kg m^{-3} for February 1991 and 1992; 26.0 kg m^{-3} for May, August, and October) to illustrate the water-mass character of the upper water column. Results from a preliminary survey in August 1990 are summarized first, with vertical sections of salinity and velocity.

4.1. August 5–10, 1990

An August 1990 survey of the Gulf of the Farallones included two cross-shelf sections that extended from Point Reyes and Point Montara, intersecting at Pioneer Seamount (Fig. 1). Station spacing varied from 1.7 to 12.4 km and was closest over the upper slope. Winds were weakly equatorward during this cruise (Gezgin, 1991).

A poleward jet was evident over the continental shelf and slope (Fig. 4), with maxima of 20–40 cm s^{-1} near the coast and over the upper slope. A jet of recently upwelled water, a feature often seen in AVHRR images, crossed the northern section with an equatorward component of flow about 20–50 km west of the shelf break, and exited the southern section as a surface-intensified current 50–60 km from the break. Strong ($>$ 20 cm s^{-1}) poleward flow also was observed throughout the water column 60–70 km from the shelf break. The velocity field featured considerable submesoscale [O(10 km)] structure (Gezgin, 1991).

Water with a relatively high percentage of Pacific Equatorial Water (PEW) is typically found over the slope at this time of year, corresponding to a salinity maximum in the upper 150–200 m over the outer slope (Fig. 5) and high spiciness anomaly (Gezgin, 1991). Isohalines sloped downward toward the slope, consistent with a geostrophic poleward current. On a larger scale, the halocline upwelled toward the coast, a feature common to the California Current System. A salinity minimum of $S = 33.3$–33.4 flowed south over the outer shelf, and much fresher water ($S < 33.1$) was observed at a distance greater than 40 km west of the shelf break. These salinities

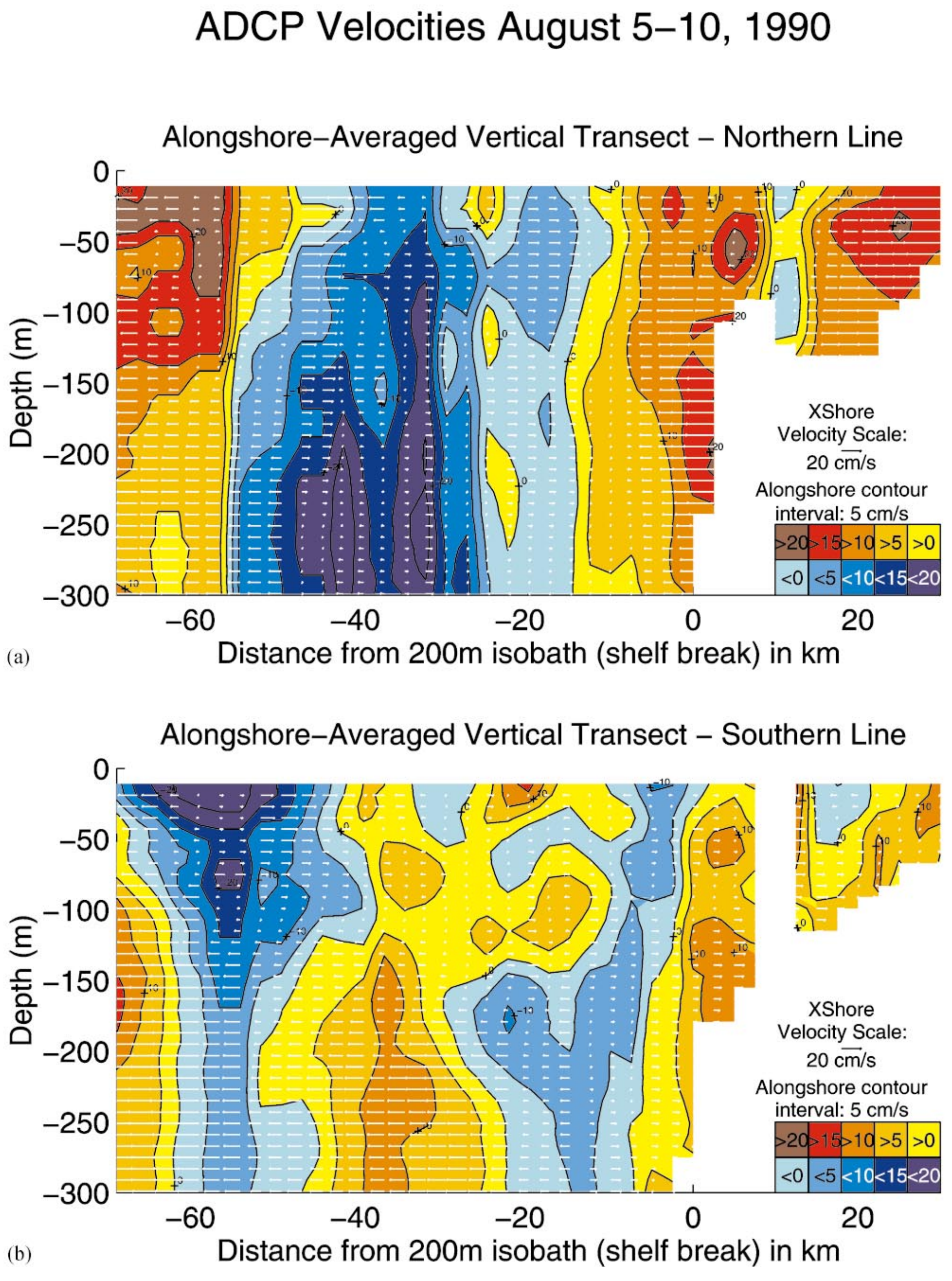


Fig. 4. August 5–10, 1990, ADCP velocity for a) northern and b) southern lines. Contours denote alongshore isotachs; positive values (red shades) denote poleward flow. Contour interval is 5 cm s^{-1}. Arrows represent cross-shore component of velocity; 20 cm s^{-1} scaling arrow shown.

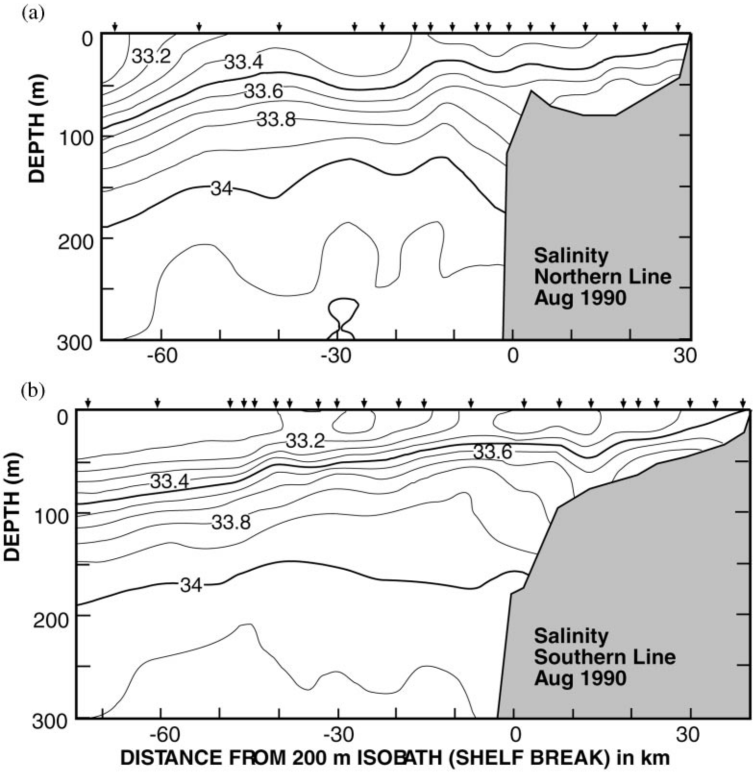


Fig. 5. August 5–10, 1990 detided cross-section salinity for (a) northern and (b) southern lines. CTD station locations shown along top of figures. Contour interval is $S = 0.1$.

identify negative or low positive spiciness anomaly ("bland") water relatively high in Pacific Subarctic Water (PSAW), and characterize the southward-flowing California Current. An extrusion of California Current surface water was seen advecting into the Gulf south of the Farallon Islands during this survey. This region of onshore flow was marked by a lens of relatively warm (from AVHRR images) and fresh ($S < 33.3$) water, resulting in a net onshore freshwater flux (Gezgin, 1991). AVHRR imagery from this time supports this idea.

4.2. February 13–18, 1991

Strong (> 40 cm s^{-1}) poleward flow (hereafter called the Slope Countercurrent or SCC) was evident over the continental slope, and equatorward flow was present over much of the continental shelf (Fig. 6a and b). Throughout the Gulf, higher velocity regions ("jets") produced considerable horizontal shear. Poleward velocities were surface-intensified. Poleward flowing waters were relatively warm and fresh near the surface (Fig. 7). Although the speed decreased to 5–10 cm s^{-1} at 300 m, the direction was generally poleward over the slope.

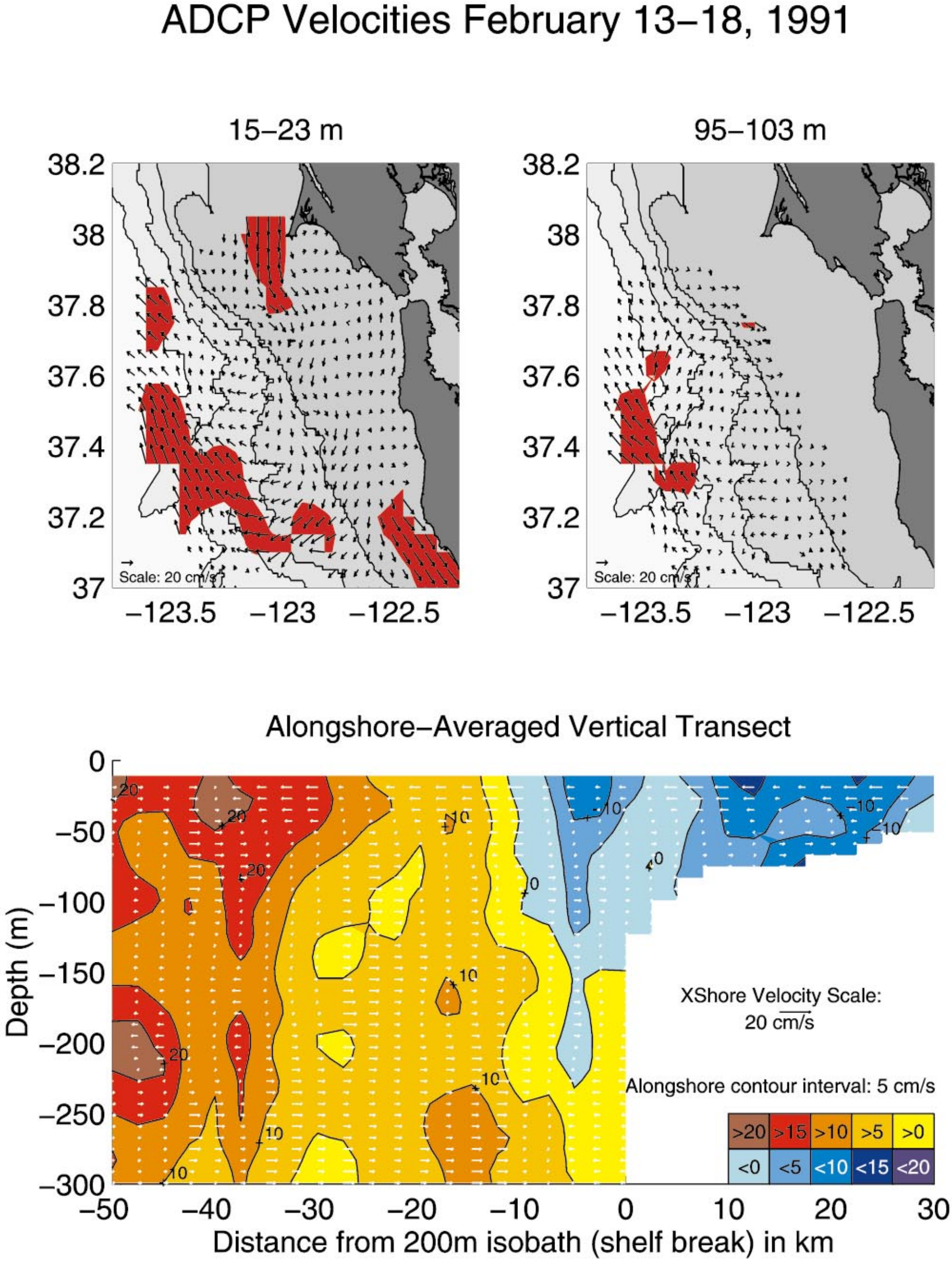


Fig. 6. ADCP velocities, February 13–18, 1991 (a) Upper left panel, $0.05° \times 0.05°$ horizontal grid of ADCP velocities in the 15–23 m depth bin. Regions of speeds greater than 15 cm s^{-1} are shaded in red to highlight the jets. Bathymetry is the same as for Fig. 1. (b) Upper right panel, same as (a) except velocity bin is 95–103 m (c) Lower panel, alongshelf-averaged transect on a 8 m depth by 2.5 km cross-shore distance grid. Contours denote alongshore isotachs; positive values (red shades) denote poleward flow. Contour interval is 5 cm s^{-1}. Arrows represent cross-shore component of velocity; 20 cm s^{-1} scaling arrow shown.

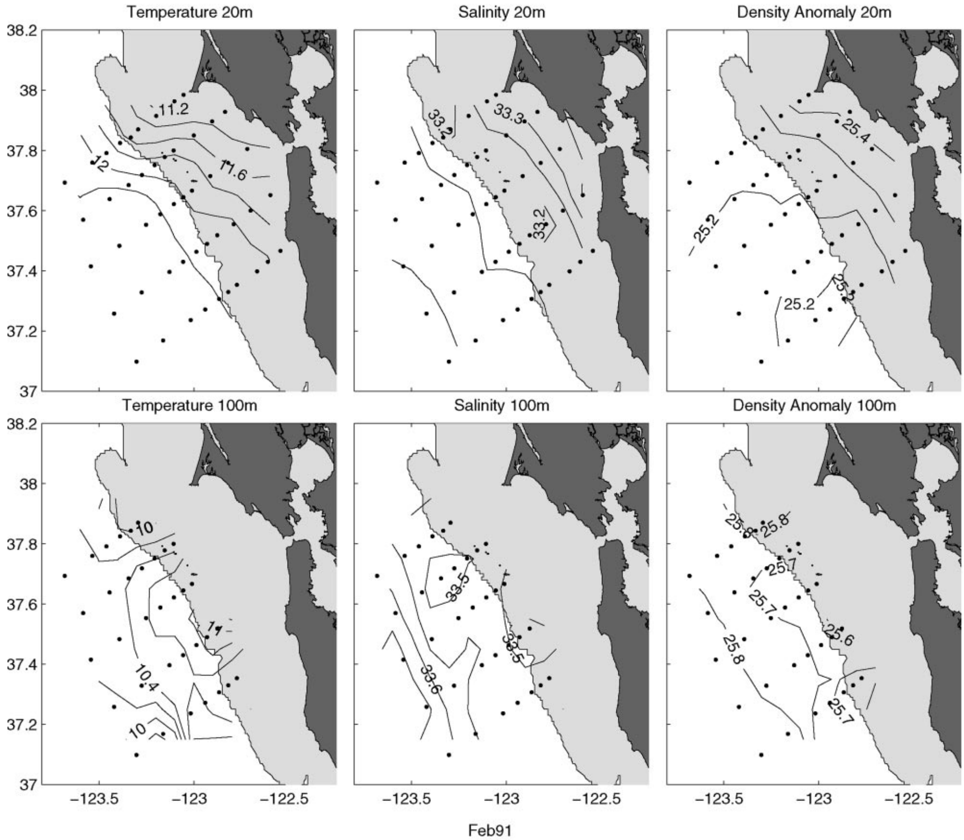
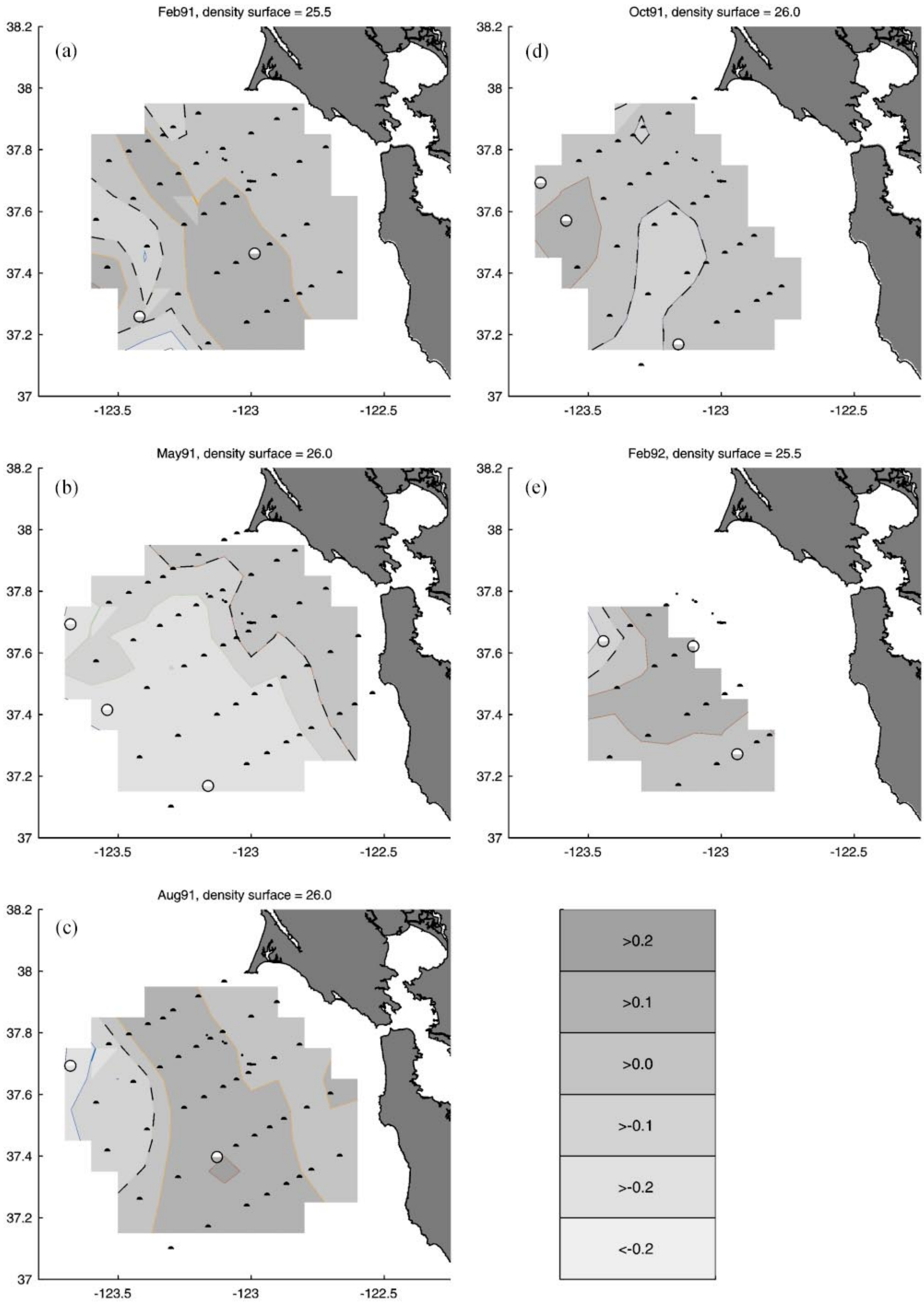


Fig. 7. Temperature, salinity, and density anomaly, at 20 m depth (upper panels) and 100 m depth (lower panels), February 13–18, 1991. Contour intervals are 0.2°C, $S = 0.05$, and 0.1 kg m^{-3}, respectively. Area less than 200 m depth shaded.

Nearshore, water entered the Gulf from the north around Point Reyes (Fig. 6a). This > 40 cm s^{-1} jet contained relatively cool, salty water (Fig. 7), which may have been upwelled north of the Gulf and advected by the equatorward shelf current typically found between Point Arena and Point Reyes (Huyer and Kosro, 1987). The jet decelerated after entering the Gulf and meandered southward at 10–15 cm s^{-1}. Part of this flow recirculated; the remainder accelerated and exited the Gulf in the south. Most of the cool, saline water remained near the coast, but cool filaments

Fig. 8. Spiciness anomaly on isopycnal surfaces. (a) February 1991, 25.5 kg m^{-3} (50–80 m nominal depth range). (b) May 1991, 26.0 kg m^{-3} (30–100 m). (c) August 1991, 26.0 kg m^{-3} (80–100 m) (d) October 1991, 26.0 kg m^{-3} (100–120 m). e) February 1992, 26.0 kg m^{-3} (90–110 m). Broken lines denote zero spiciness anomaly contours. Darker shades denote positive anomalies. Open circles denote CTD stations whose temperature-salinity relationships are shown in Fig. 9.


Feb91, density surface = 25.5
(a)
May91, density surface = 26.0
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Aug91, density surface = 26.0
(c)
Oct91, density surface = 26.0
(d)
Feb92, density surface = 25.5
(e)
38.2
38
37.8
37.6
37.4
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-122.5
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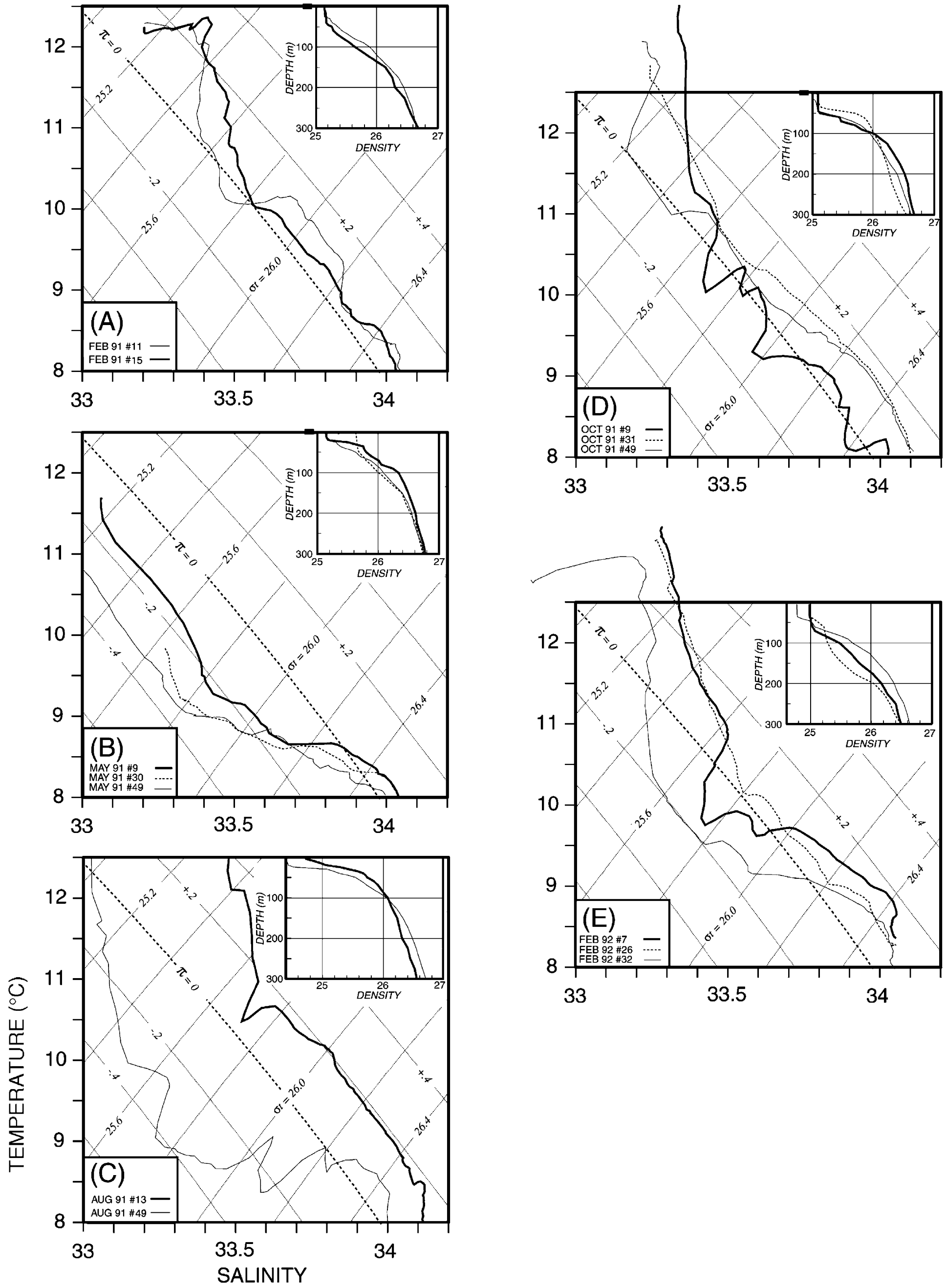
(A)
FEB 91 #11
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MAY 91 #49
(C)
AUG 91 #13
AUG 91 #49
(D)
OCT 91 #9
OCT 91 #31
OCT 91 #49
(E)
FEB 92 #7
FEB 92 #26
FEB 92 #32
π = 0
σt = 26.0
25.2
25.6
26.4
-.2
-.4
+.2
+.4
DEPTH (m)
DENSITY
TEMPERATURE (°C)
SALINITY

extended seaward of Point Reyes and Point Montara. The shelf flow was generally barotropic, although high velocity regions were surface-intensified. AVHRR SST imagery (Steger, 1997; Fig. 4 and 14c) showed a pattern similar to temperature at 20 m (Fig. 7, upper left panel).

The cross-shelf flow conforms to the classic model of Ekman circulation expected for the upwelling-favorable winds during this survey (Fig. 6c). Offshore flow decreased with depth in the upper 50 m over the shelf and slope (Fig. 6a and c). Below 50 m depth, the flow had an onshore component (Fig. 6b and c).

The shear between the shelf and slope flow in the upper 100 m formed an anticyclonic eddy-like circulation at least 40 km across, centered near 37.5°N, 123.2°W (Fig. 6a and b). Its center featured the highest spiciness (warm, saline) anomalies seen on this cruise (Fig. 8a), maximum ($\pi > 0.2$) in the 25.2–25.6 kg m^{-3} isopycnal range, around 50–75 m depth (Fig. 9a, bold curve). This positive anomaly characterizes a near-surface slope water mass containing a higher percentage of PEW, as found in the California Undercurrent. However it appears to be distinct from the spicy Undercurrent water at 100–200 m (Fig. 9a, light curve). Moored current-meter data (Kinoshita et al., 1992) suggest this eddy remained in the study region until late April, although its position fluctuated over time. Relatively bland surface water associated with the California Current was found on the offshore side of the eddy (Fig. 8a and Fig. 9a, light curve).

This eddy was very similar to anticyclones found seaward of this area in March 1992 (Lynn and Kosro, pers. comm.) and in summer 1993 (Huyer et al., 1998). Those observed by Huyer et al. were about the same diameter and featured similar velocity, temperature, and spiciness values on 25.4–25.6 kg m^{-3} isopycnal surfaces. However the offshore summer anticyclones extended deeper and the depth of maximum spiciness was 100–200 m, versus < 100 m for the February 1991 survey. The core of the poleward jet, in contrast, contained low or negative spiciness anomalies (relatively cool and fresh on isopycnal surfaces; Fig. 8a and Fig. 9a, light curve), implying it was carrying a relatively high percentage of PSAW from the California Current. Spiciness anomalies on the 26.4 isopycnal (ca. 200 m) increased offshore and gave no evidence of the eddy (Ramp et al., 1997).

Huyer et al. (1998) suggest the eddies they observed originated over the slope in mid-winter. Without dissolved oxygen measurements, it is not possible to define the source of these water masses. However Lynn and Simpson (1990) identified similar

Fig. 9. Temperature-salinity relationships for 1991–1992 surveys, representing water types associated with circulation features. Dashed diagonal lines note isopycnals (running lower left to upper right), and constant spiciness anomaly (spicy water toward lower left and bland water toward upper right). In general, bold (light) curves identify Slope Countercurrent (California Current) water. (a) February 1991; offshore (#11; 37°15.5′N 123°25.2′W) and anticyclone (#15; 37°27.8′N 122°59.2′W) (b) May 1991; upwelling jet (#30; 37°24.6′N 123°32.5′W), cyclone (#9; 37°10.2′N 123°9.7′W), and anticyclone (#49; 37°41.5′N 123°40.8′W). (c) August 1991; slope (#13; 37°23.7′N 123°7.6′W) and offshore (#49; 37°41.6′N 123°40.7′W) (d) October 1991; cyclone (#9; 37°10.1′N 123°9.4′W) and anticyclone (#31; 37°34.1′N 123°35.1′W; and #49; 37°41.6′N 123°40.8′W). (e) February 1992; inshore (#7; 37°16.3′N 122°56.4′W), slope (#26; 37°37.5′N 123°6.1′W), and offshore (#32; 37°38.3′N 123°26.4′W).

anticyclonic eddies off southern California, and ascribed a slope water source to them. Low oxygen was a signature of the southern California eddies as well as those observed off central California (Lynn and Kosro, pers. comm.).

4.3. May 16–21, 1991

The flow regime was quite different in May. Currents (Fig. 10), hydrography (Fig. 11) and AVHRR imagery (Fig. 12) showed cool, saline water, probably recently upwelled, flowing alongshelf south of Point Reyes. Near the Farallon Islands, this upwelling jet water flowed southwest, accelerating to > 40 cm s^{-1} before leaving the survey area near 37.4°N. It gradually mixed with warmer, fresher water that converged onto this jet from both the north and south, with velocities also > 40 cm s^{-1}. An AVHRR image from May 15, just prior to the cruise (Fig. 12), revealed that the cool, saline water was part of a large plume of upwelled water extending from north of Point Reyes, southwestward through the Gulf. The signature of the spicy anticyclonic eddy from February had disappeared from the region (Fig. 8b and Fig. 9b). Spiciness was negative (bland) over the slope and weakly positive over the shelf.

The satellite image (Fig. 12) implied an interaction of the upwelling jet with the California Current to form a hammerhead-shaped feature in SST. This created a submesoscale vortex pair, the inshore portion of which was captured in the slope ADCP data (Fig. 10a and b). This surface pattern occurs repeatedly in spring and summer in this area (Parker, 1996; Baltz, 1997). Both eddies had relatively fresh (Fig. 11) and bland ($\pi < -0.2$) near-surface centers (Fig. 9b). For comparison, Huyer et al. (1998) found June anomalies of $\pi \approx -0.3$ at 36°N.

Isopycnals diverged away from (converge toward) the horizontal center of the anticyclone (cyclone). The lens of the northern anticyclone was slightly shallower (ca. 50 versus 100 m) and typically $\pi = 0.1$ higher than its southern partner (Fig. 8b). However, the anticyclonic eddy was surrounded by a larger percentage of PSAW from offshore as well as from the upwelling jet. This intrusion of PSAW water was restricted to above the 26.4 kg m^{-3} isopycnal surface, the upper 150 m (cf. Ramp et al., 1997). Positive spiciness anomalies, probably the signature of the California Undercurrent, were found below this surface.

The Slope Countercurrent (SCC) was more baroclinic in May than February (cf. Figs. 6 and 10). At 100 m, the flow over the slope was generally poleward although weak and meandering (Fig. 10b). The offshore flowing upwelling jet was still fairly strong at 100 m, but the equatorward jet in the north was barely evident. The upwelling jet obscured the poleward slope current, particularly near the surface where the circulation of the eddy pair was strongest. Within about 20–30 km of the shelf break, the slope current had a northward component of 5–20 cm s^{-1}.

Upwelling-favorable winds are strongest during this season (Fig. 2), and the effect on water mass characteristics is marked. The upper 100 m was $1 - 3$°C cooler and $S = 0.1$–0.5 more saline (Fig. 11) than in February, and substantially more bland (Fig. 8b and 9b). Even at 200 m depth, waters were nearly 1°C cooler and $S = 0.05$–0.1 saltier due to the uplifting of isopycnal surfaces associated with coastal upwelling (Steger, 1997). Compared to CalCOFI climatologies, the region was unseasonably

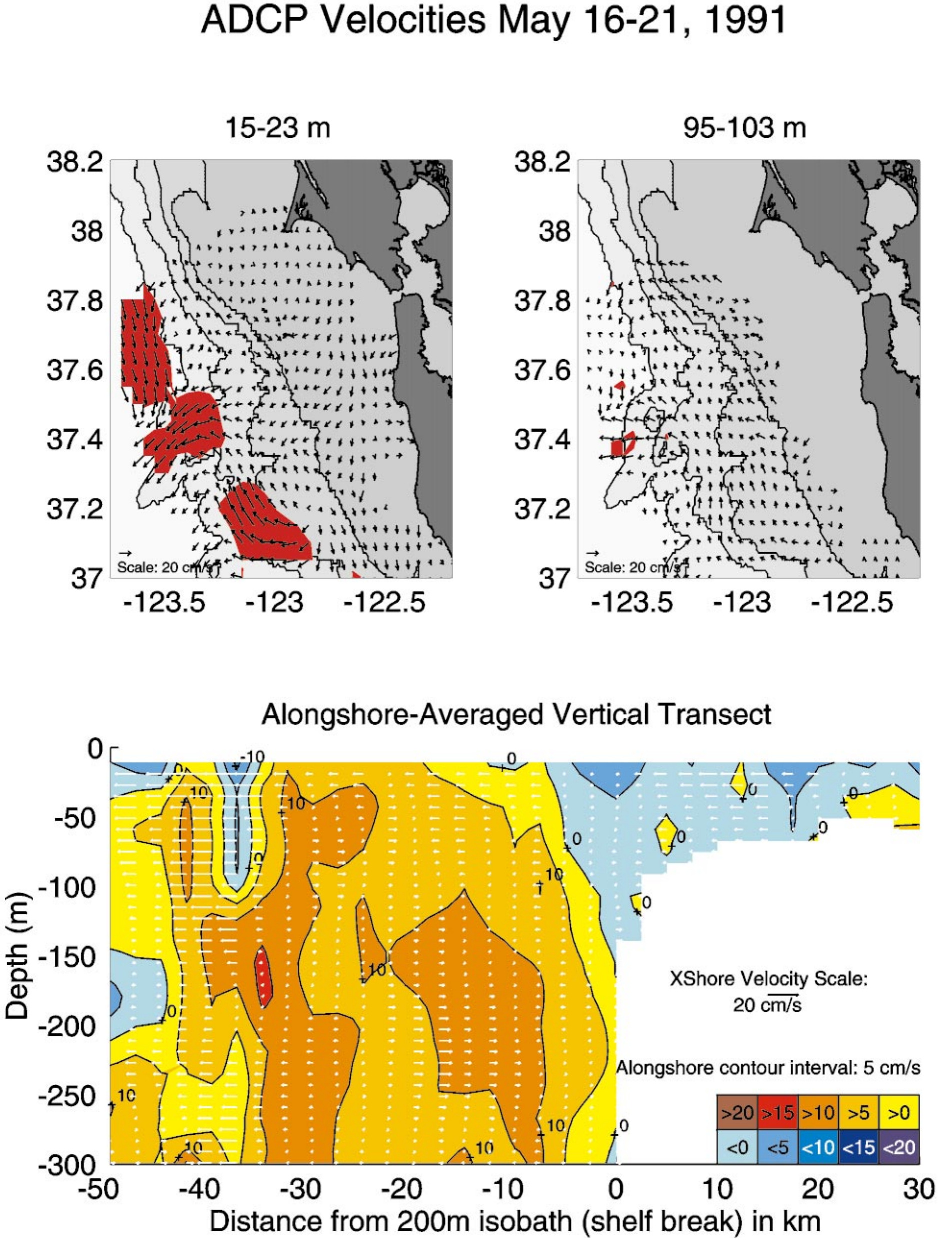

Fig. 10. ADCP velocities, May 16–21, 1991. Otherwise same as Fig. 6.

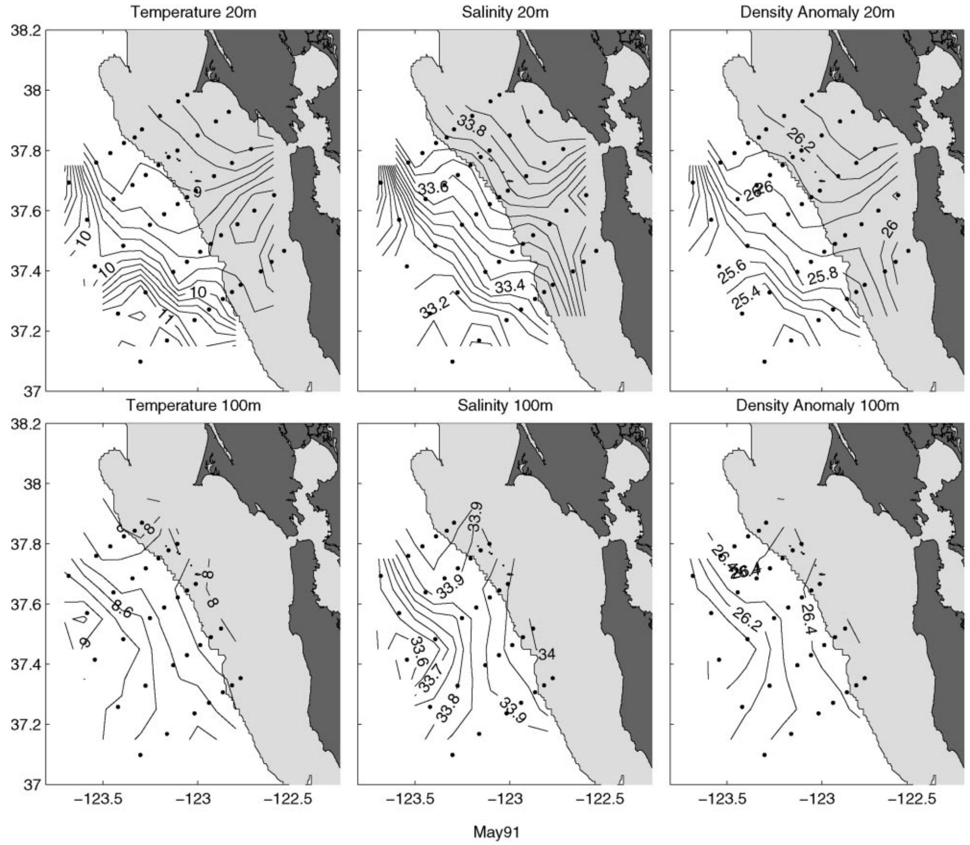

Fig. 11. Same as Fig. 7, for May 16–21, 1991.

cool and saline (Ramp et al., 1995,1997). As seen during the upwelling-favorable conditions of February, cross-shore velocities (Fig. 10c) were directed offshore in the surface Ekman layer (to ca. 50 m), and weakened with depth.

4.4. August 12–18, 1991

A strong continuous SCC dominated the outer slope region. Unlike earlier in the year, this flow was greatest at 100 m depth rather than at the surface (Fig. 13a and b). A strong (20–40 cm s^{-1}) core of poleward flow, 50–200 m depth 20–40 km seaward of the shelf break, closely followed the 1000 m isobath. It gave the impression of an anticyclonic meander south of 37.5°N and a weaker cyclonic meander in the north. The core of this flow was closer to the shelf than in February, but, as seen in the previous two surveys, cross-shelf flow exceeded 10 cm s^{-1} in some areas. However, the shelf surface flow was onshore in August, a tendency expected given the downwelling-favorable wind stress at the beginning of the survey.

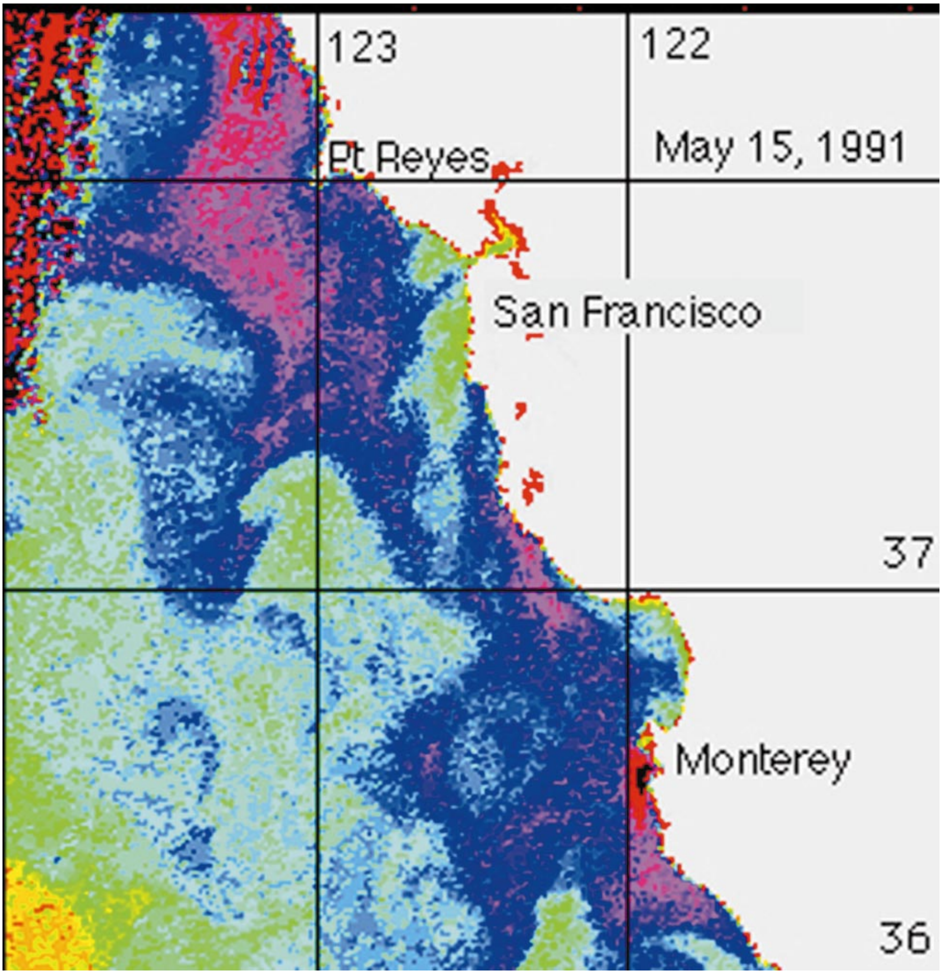

Fig. 12. 15 May 1991 AVHRR image of California Current region from Bodega Bay to Lopez Point. Relative surface temperatures are shown from cold (magenta and blue) to warm (orange and red). Clouds are masked black.

Associated with the subsurface poleward core was a region of spicy ($\pi > 0.2$) water that narrowed to the north (Fig. 8c and 9c). These were the highest anomalies noted during the five Gulf surveys. In contrast, Huyer et al. (1998) observed a lower spiciness maximum over the slope in August 1993 compared to June. Isopycnals shoaled (deepened) in the center of the SCC above (below) the 26.0 kg m^{-3} isopycnal (ca. 100 m). In addition, higher (lower) spiciness anomalies were associated with the anticyclonic (cyclonic) meanders. This signature of the spiciness field was observed to about 250–300 m (the 26.5 kg m^{-3} isopycnal). The August cruise also featured the greatest range in spiciness. Extremely bland water ($\pi < -0.3$) was observed in the

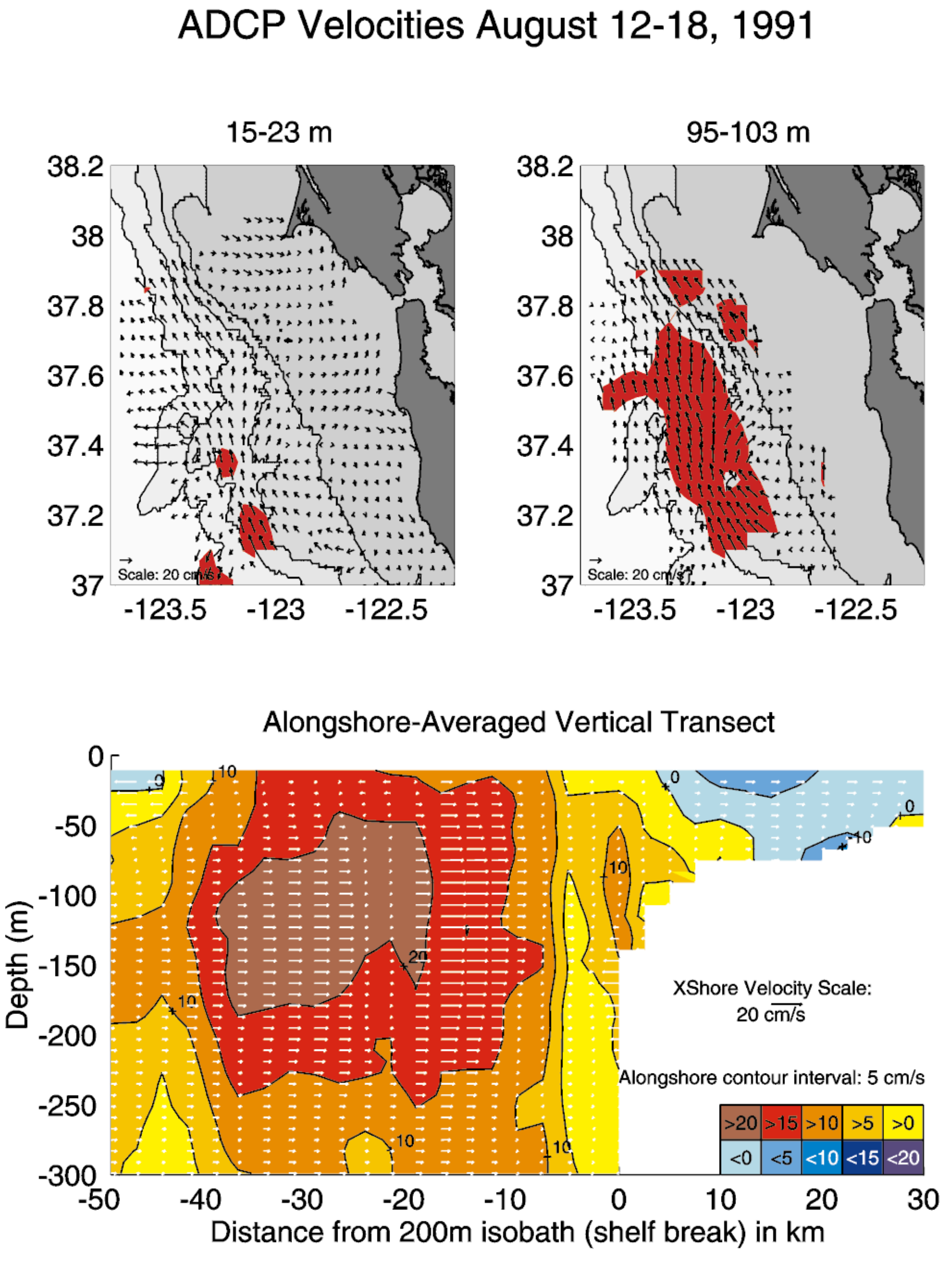

Fig. 13. ADCP velocities, August 12–18, 1991. Otherwise same as Fig. 6.

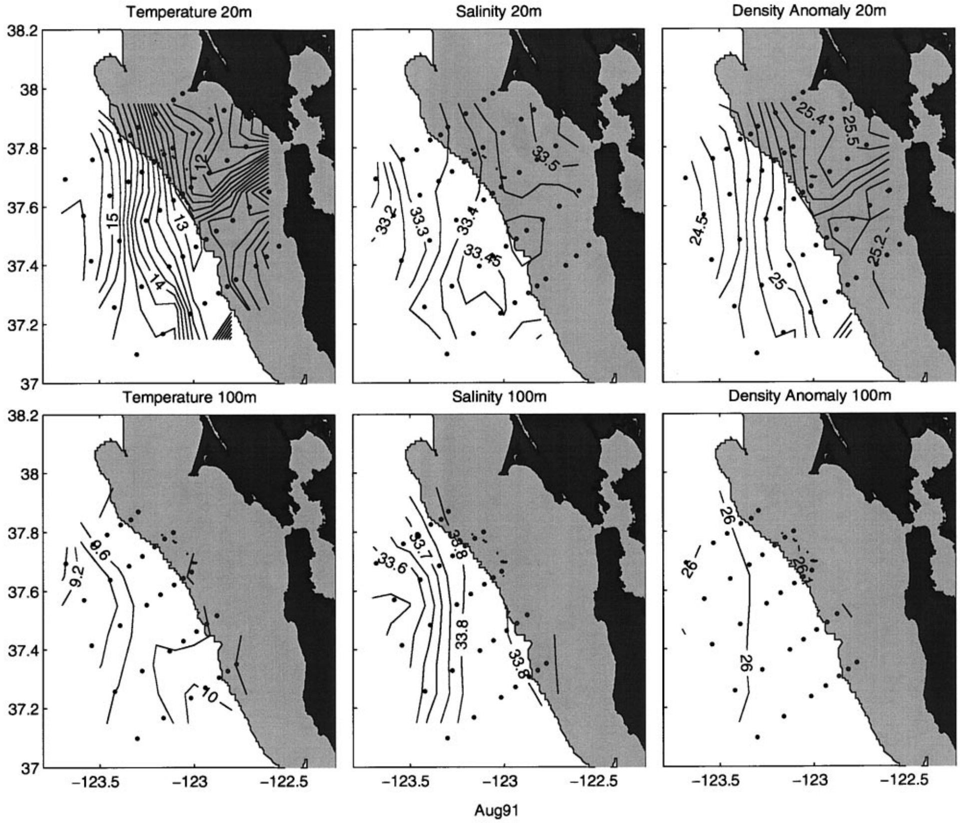

Fig. 14. Same as Fig. 7, for August 12–18, 1991.

upper 100 m seaward of the SCC (Fig. 8c and 9c), suggesting an intrusion of PSAW from the California Current, possibly associated with the cyclonic meander.

On the shelf, water entered the Gulf from north of Point Reyes and exited south near Point Montara. Coolest temperatures and highest salinities were again located south of Point Reyes (Fig. 14). However surface waters were 3°C warmer and as much as $S = 0.4$ fresher from May, indicating reduced upwelling. Buoy observations (Fig. 3) suggest August conditions were unseasonably warm. Unfortunately, no satellite imagery was available for several weeks before or after the cruise due to pervasive cloud cover.

In August, 50–200 m temperatures and salinity (Fig. 14) were similar to those seen in February. Water was warmer and slightly fresher than CalCOFI means (Ramp et al., 1997). Isopycnals below 100 m sloped steeply downward toward the coast, consistent with relaxed wind conditions and a poleward geostrophic flow.

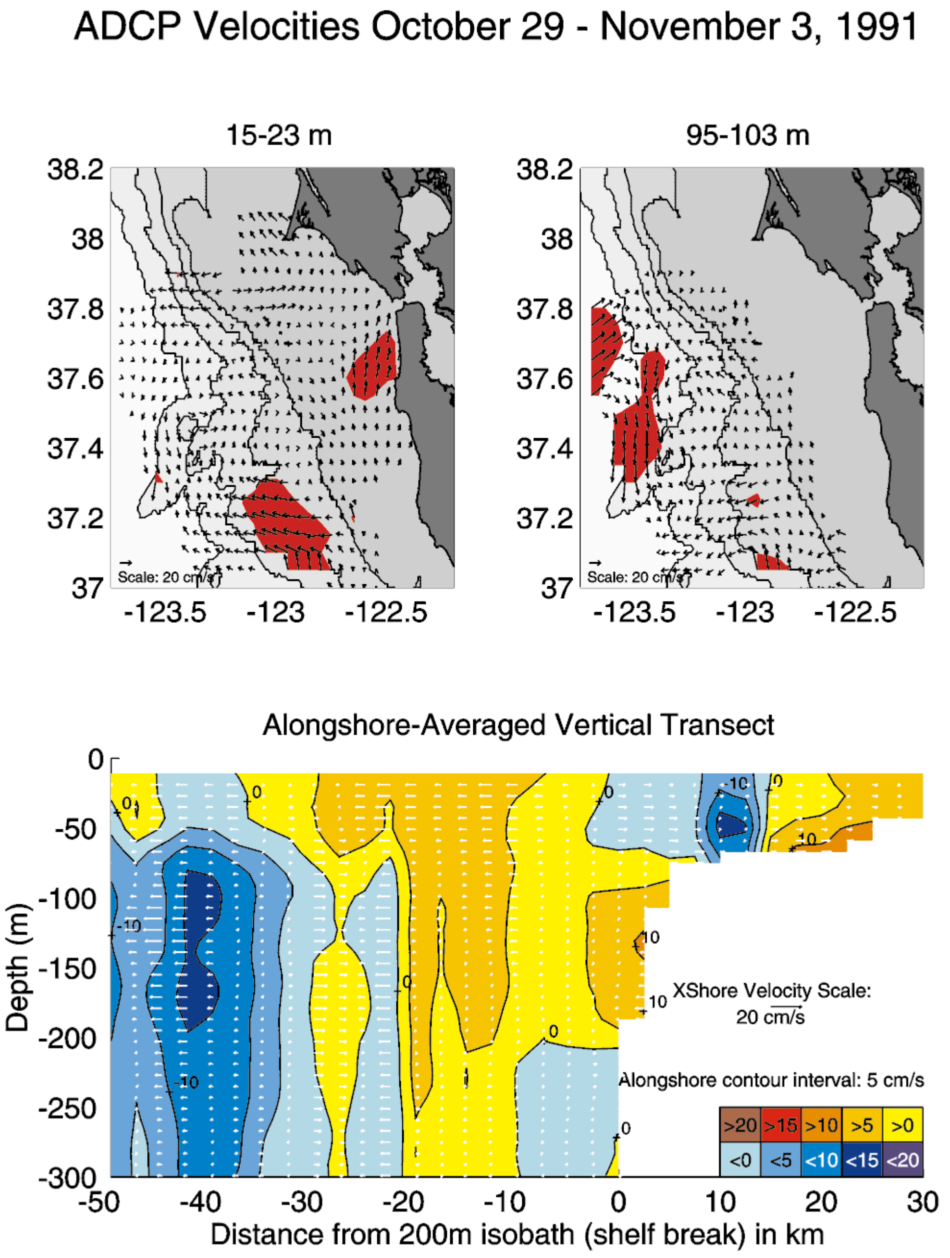

Fig. 15. ADCP velocities, October 29–November 3, 1991. Otherwise same as Fig. 6.

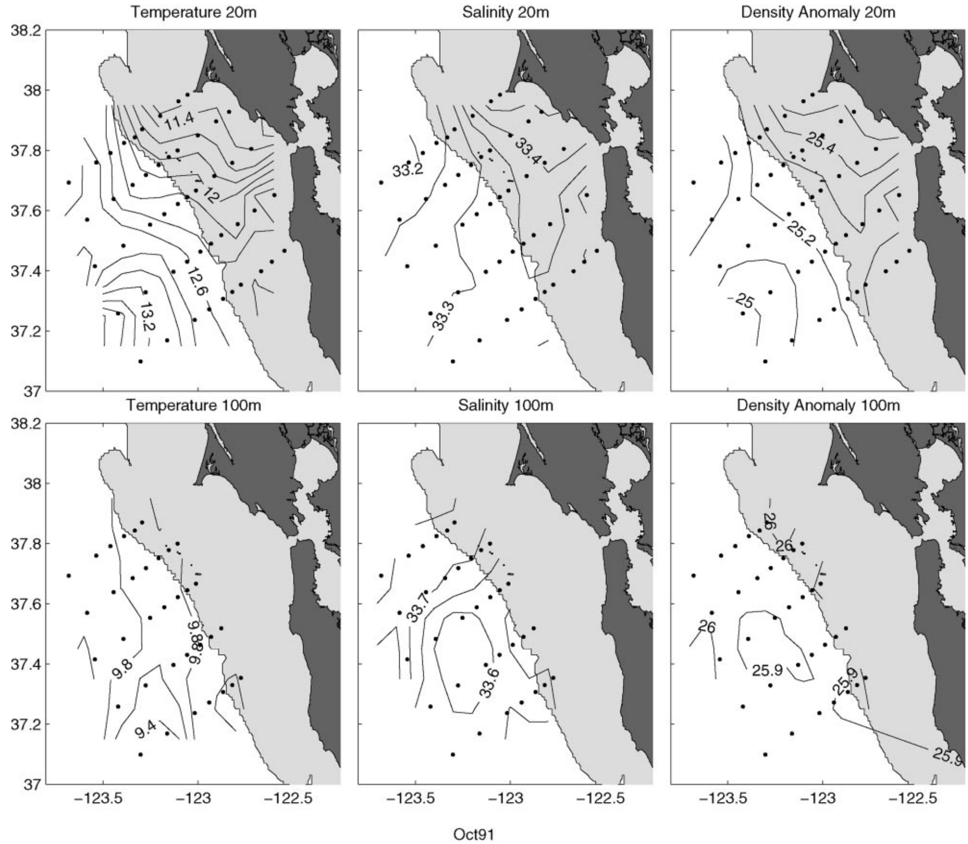

Fig. 16. Same as Fig. 7, for October 29–November 3, 1991.

4.5. October 29–November 3, 1991

Unlike the other 1991 cruises, strong poleward surface flow was seen over the shelf, entering the Gulf from the south (Fig. 15a and c). Cross-shore velocities were onshore over the shelf but offshore in the top 50 m over the slope (Fig. 15c). It is likely that the relaxation of equatorward wind stress at the onset of this survey (Fig. 2) led to this shelf circulation. However, cool saline water was present south of Point Reyes (Fig. 16), probably a remnant from the strong upwelling event prior to this cruise. Some of this water extended offshore, the remainder southeast along the shelf.

Two warm-core vortices, separated by an offshore-tending streamer of cool water, were seen as anticyclone and cyclone circulations at 100 m at 37.5°N, 123.8°W and 37°N, 123°W, respectively (Fig. 15b and 16). The SST signature of these features was present in AVHRR images (Fig. 17); the pattern was very similar to May (Fig. 12). Unlike May, however, the cool surface streamer was not affiliated with an accelerating offshore flow, and only the southern cyclonic eddy is evident in the ADCP surface

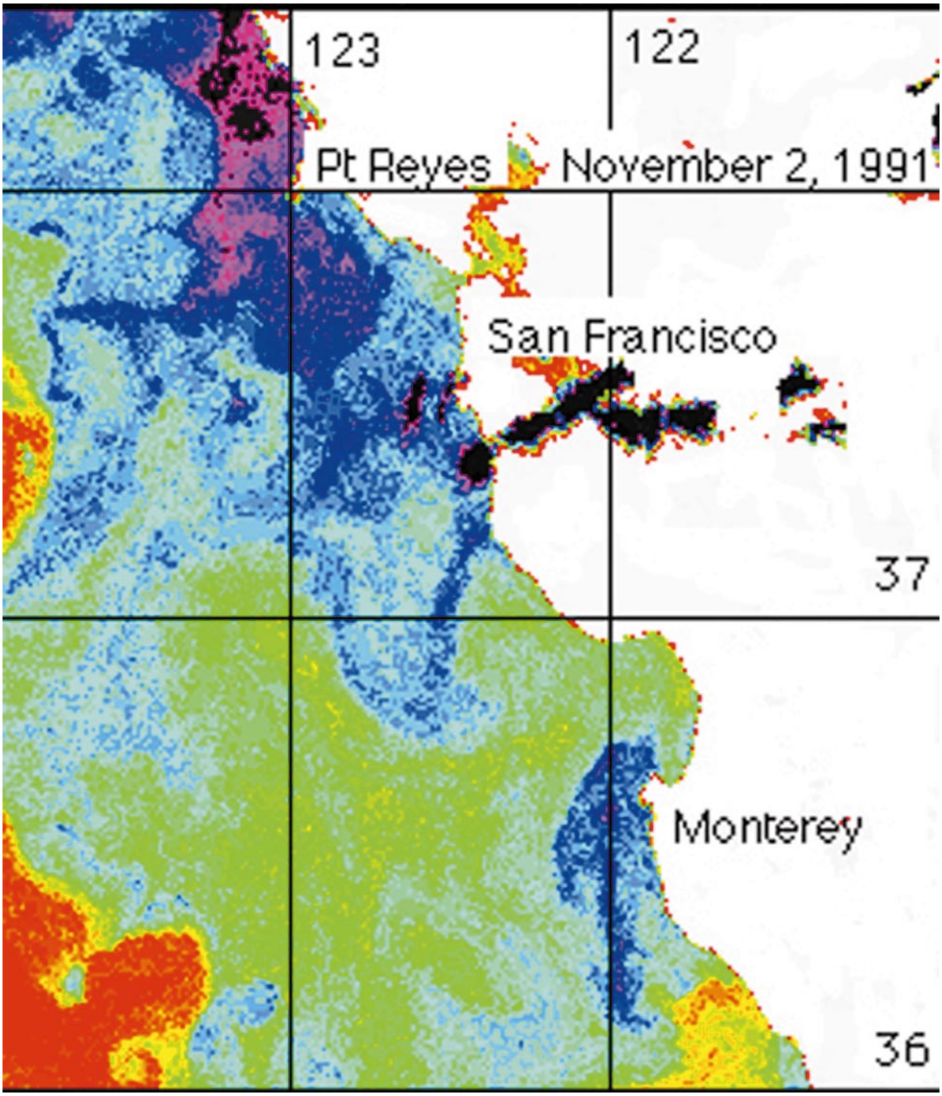

Fig. 17. 2 November 1991 AVHRR image of California Current region from Bodega Bay to Lopez Point. Otherwise same as Fig. 12.

velocity field (Fig. 15a). Both eddies and the strong offshore current were prominent at mid-depths (e.g. 100 m), in contrast with the May surface intensification. From the density and spiciness anomalies, the center of October pair was about the 26.0 kg m^{-3} isopycnal (ca. 100 m depth). The isopycnal range of their cores was 25.5–26.5 kg m^{-3}, similar to the Huyer et al. (1998) warm-core eddies. As in May, isopycnals diverged away from (converge toward) the anticyclone (cyclone) core, both above and below.

The depth range of the anticyclone's (cyclone's) lens was 50–300 m (75–200 m), based on isopycnal perturbations and spiciness anomalies.

Temperature in the upper 100 m (Fig. 16) was cooler than in August, but unchanged in deeper water. Salinity was slightly less ($S \sim 0.1$) throughout the water column. Below the mixed layer, the anticyclonic (cyclonic) eddy was associated with spicy (bland) water (Fig. 8d and Fig. 9d). This suggests the northern anticyclonic eddy entrained PEW, while the core of the southern eddy contained more PSAW, a pattern observed in May nearer the surface. The pair were visible to at least 500 m, based on isopycnal displacement and spiciness anomalies. The anticyclone seen here looks remarkably similar to those described by Huyer et al. (1998). High variability in spiciness throughout the pycnocline (Fig. 9d), a pattern also evident in August and February 1992, suggests interleaving of California Current and SCC waters over the slope.

4.6. *February 7–17, 1992*

The circulation and hydrography in February 1992 were very different from the 1991 cruises, and in strong contrast to February 1991. A tropical El Niño event developed in the interim, affecting the basin-scale distribution of ocean characteristics. A particularly strong (> 40 cm s^{-1}) and coherent SCC was seen in the upper 150 m (Fig. 18). The flow and water mass character displayed many of the features seen in the previous August. Again a spicy (PEW) poleward flow penetrated the survey region (Fig. 8e and 9e). AVHRR SSTs were warmest over the slope (Fig. 19), with cooler water both inshore and offshore of the maximum flow in the SCC. The region of maximum SST appears to narrow off Point Reyes, coinciding with an acceleration in the SSC.

Spiciness anomalies were high (Fig. 8e and 9e), corresponding to a $\sim 1^\circ$ warming of the upper ocean from February 1991 (cf. Figs. 7 and 20). Salinities on pressure surfaces were $S \sim 0.1$ fresher than in February 1991, but were not enough to counter the effect of warming on spiciness. Very warm, fresh anomalies (cf. CalCOFI climatology) were found throughout the water column, with the greatest temperature (salinity) anomalies occurring at 50–100 m (100–150 m) (Ramp et al., 1997). Lynn et al. (1995) observed a similar pattern off central and southern California in early 1992, and attributed it to an onshore displacement of the California Current. This pattern has been noted in previous El Niños (Simpson, 1992; Lynn et al., 1995).

High spiciness anomalies extended well below 100 m (Fig. 9e). However, the spiciness maximum below 200 m was part of a deep eddy that did not affect the upper 100 m (Ramp et al., 1997). As in August, strong cross-shore gradients in temperature and salinity, separating the California Current (PSAW) and SCC (PEW), were found in conjunction with the core of the poleward jet. This jet was associated with the warmest and freshest water seen at mid-depth in all five cruises. The bland anomalies in the 25.5–26.0 kg m^{-3} isopycnal range (100–150 m) (Fig. 9e) were associated with a strong onshore current, an intrusion of the California Current onto the slope coincident with the cyclonic meander in the ADCP fields south of 37.5°N (Fig. 18).

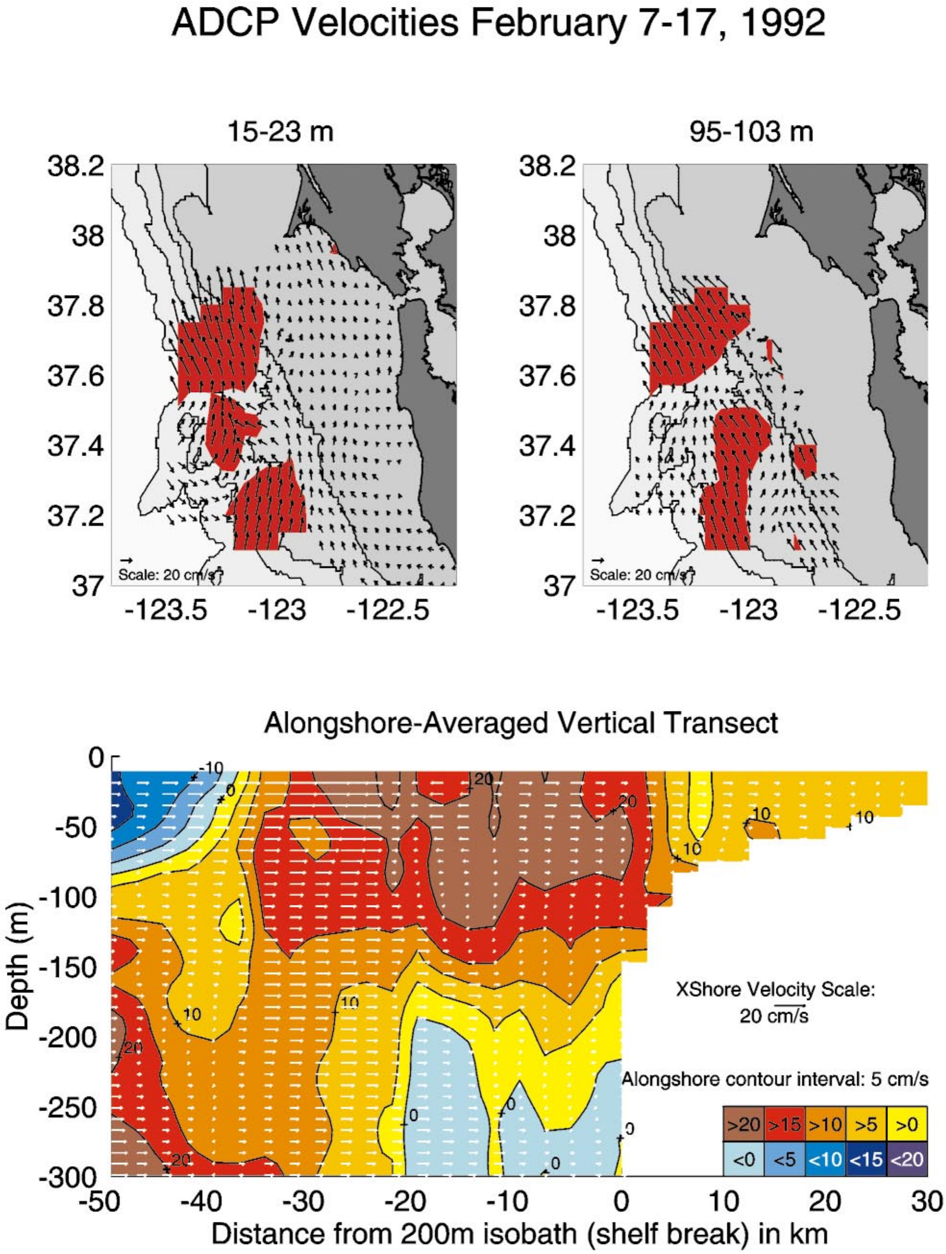

Fig. 18. ADCP velocities, February 7–17, 1992. Otherwise same as Fig. 6.

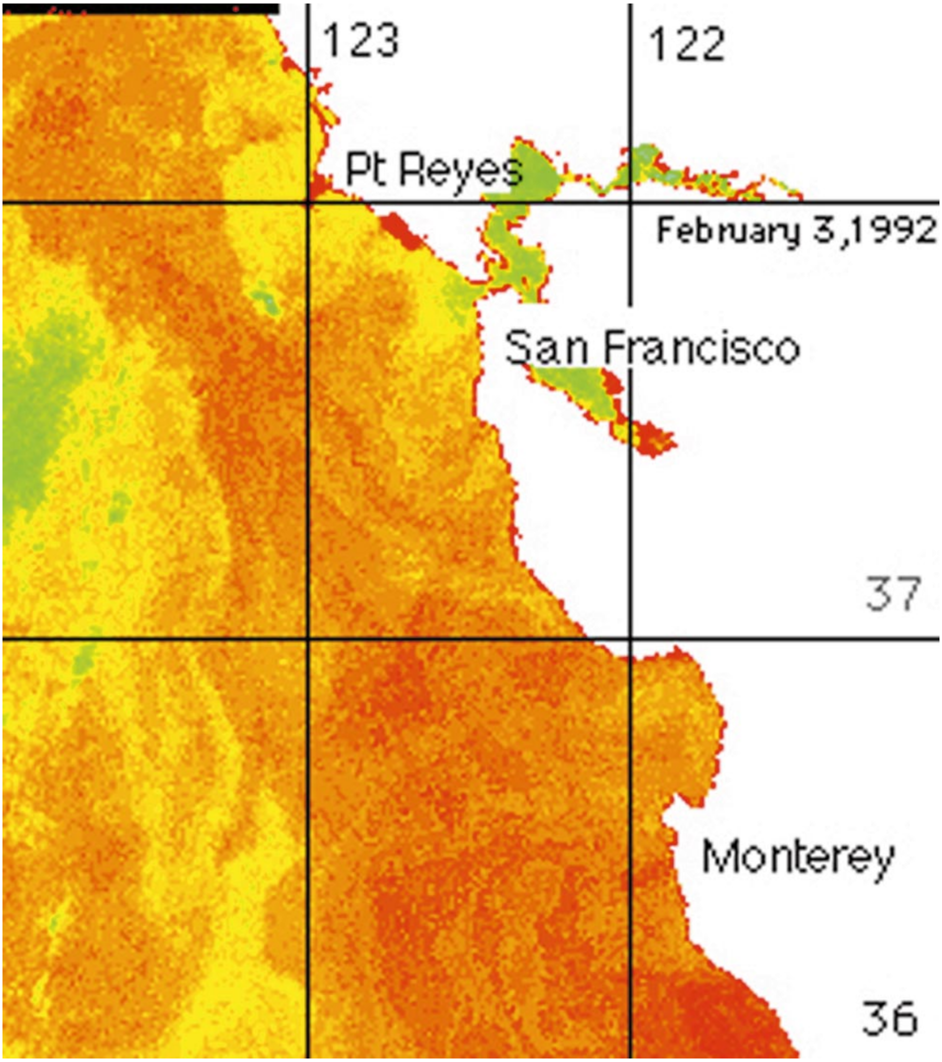

Fig. 19. 3 February 1992 AVHRR image of California Current region from Bodega Bay to Lopez Point. Otherwise same as Fig. 12.

4.7. Transports

A simple box model for the Gulf, subdivided into slope and shelf regions, gives an idealized model of the regional circulation. Transports were calculated by summing the ADCP velocities over the horizontal and vertical extent of each side. The February 1992 box is smaller because the northern leg and offshore stations were not occupied. Box model methods and results are detailed in Steger (1997). Fig. 21

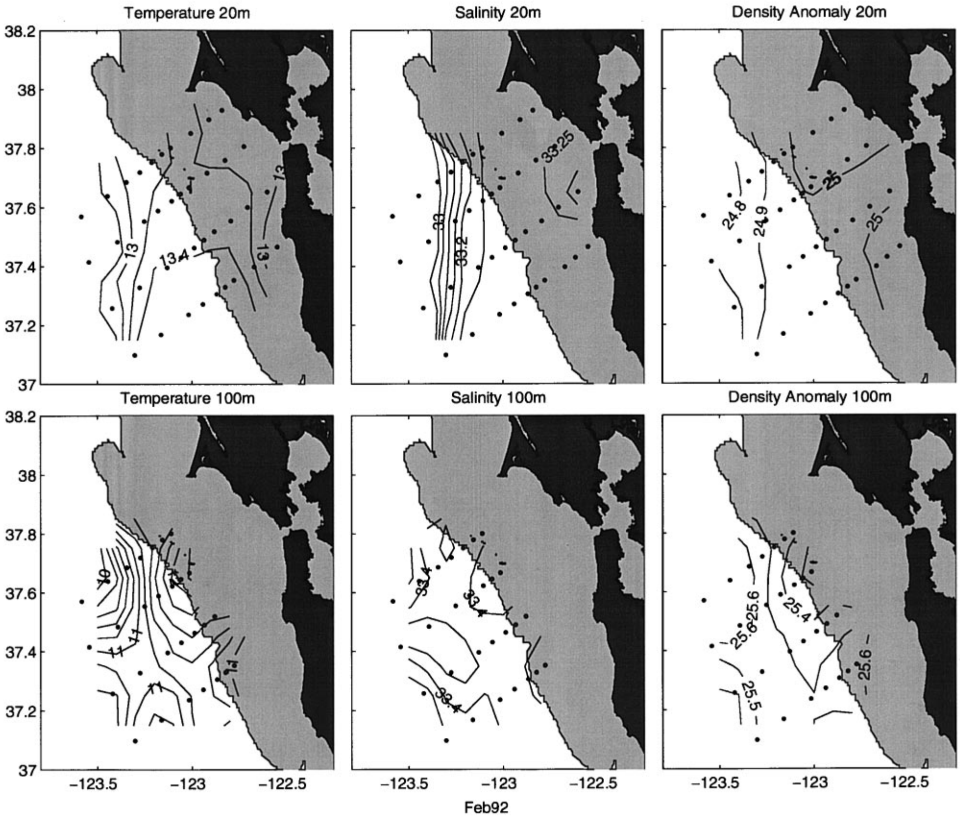

Fig. 20. Same as Fig. 7, for February 7–17, 1992.

compares the transports averaged for the four 1991 cruises to the February 1992 values.

The average net transport into and out of each box should be zero provided evaporation balances precipitation and runoff, and there is no sea level change. However, net transport into a box during a cruise did not equal total outflow. Reasons for this include ADCP measurement errors, lack of measurement synopticity, and lack of near-surface (0–7 m) and bottom (within 10% of the total depth) ADCP measurements. The area-averaged net velocity from the five cruises, which can be taken as an upper limit error, is 0.6 cm s^{-1}, well below the ~ 2 cm s^{-1} estimated error for ADCP data collected from a vessel moving at 10 knots (E. Firing, U. Hawaii, pers. comm.).

The transport pattern through the Gulf was persistent, with no discernible seasonal signal. Net transport was always poleward over the slope. About 1–3 Sv entered from the south; about one-third of this exited offshore and the remainder to the north. Transport along the shelf was much smaller, typically less than 0.1 Sv. The mean shelf

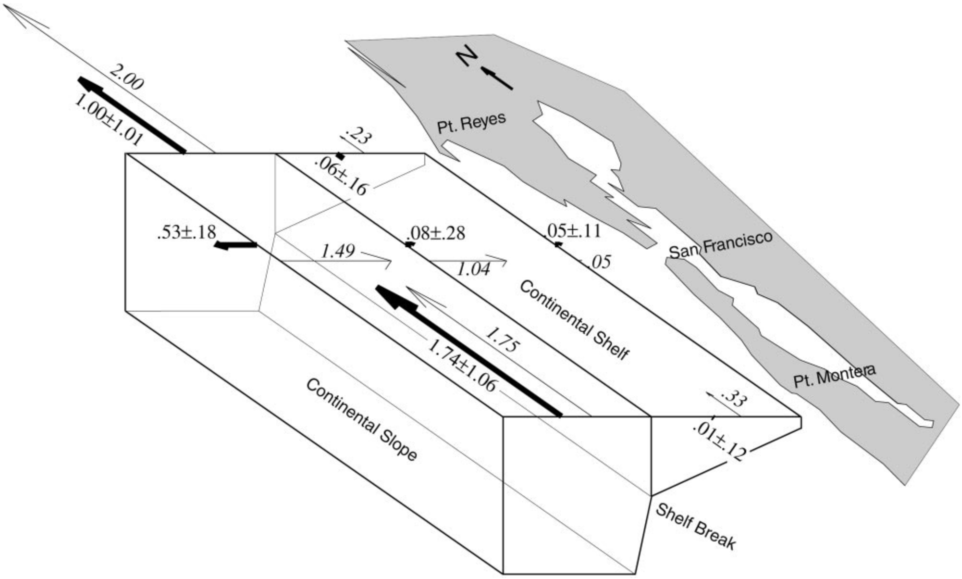

Fig. 21. Transports through the Gulf, separated into shelf and slope regions. Arrows show net transport (in Sv) normal to each plane of each region, calculated by summing ADCP velocities over the horizontal and vertical extent of each side for each survey. Bold arrows (and accompanying values) denote mean ($\pm$ standard deviation) transports from four 1991 surveys. Lighter arrows and italicized values denote transports for February 1992. Refer to text and Steger (1997) for additional details.

transport was near-zero, probably because the direction of flow changed efficiently from survey to survey in response to synoptic wind fluctuations. In nearly all cases, the direction of flow normal to the sides of these boxes did not change with depth. Although covering a different area, transports during August 1990 were poleward and very similar in magnitude (Gezgin, 1991). October was the lone exception; there was considerable small-scale variability in direction over both the slope and shelf, leading to weak (0.8 Sv) net poleward transport into the region.

The February 1992 poleward transport through the shelf and slope was extremely strong (Fig. 21). While transport into the slope was similar to the other surveys, there also was a 1.5 Sv transport from offshore, leading to a greater outflow to the north. Transport was convergent onto the shelf and very strong, especially considering the alongshore legs were 25% shorter.

4.8. Residence times

Dividing the transport into or out of the region by the Gulf's volume produces a lower-bound estimate of the time required to completely flush the Gulf. The mean residence time for the region was about one week, with a range of about 2–13 d. Residence times have no clear seasonal signal. Despite a much smaller volume, the shelf residence time was only slightly less than that of the slope region. The

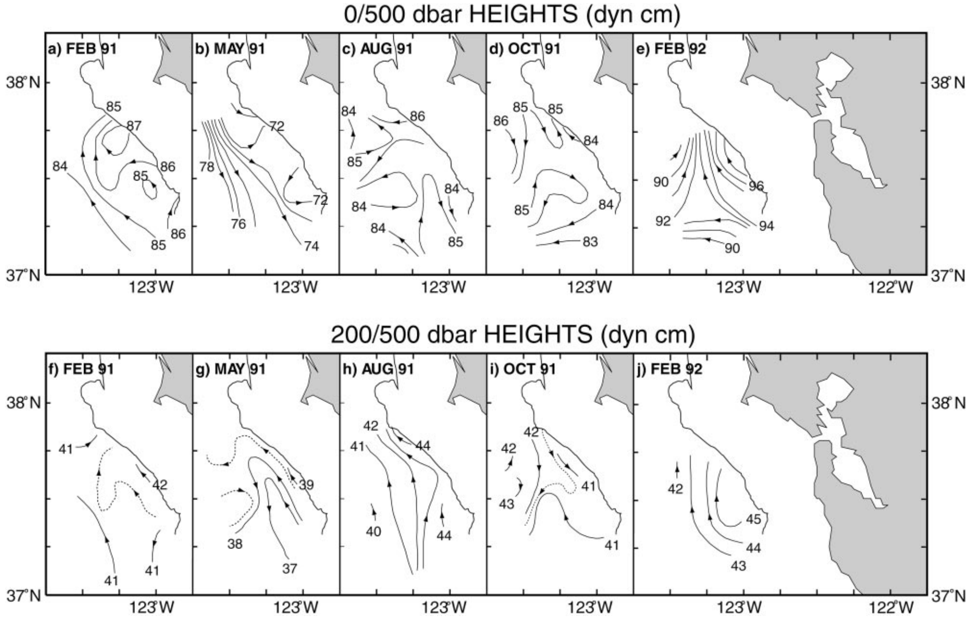

Fig. 22. Dynamic height anomalies, surface relative to 500 dbar. (a) February 13–18, 1991. (b) May 16–21, 1991. (c) August 12–18, 1991. (d) October 29–November 3, 1991. (e) February 7–17, 1992. Dynamic height anomalies, 200 dbar relative to 500 dbar. (f) February 13–18, 1991. (g) May 16–21, 1991. (h) August 12–18, 1991. (i) October 29–November 3, 1991. (j) February 7–17, 1992.

residence time for August 1990 was 3 d, but the numbers are not completely comparable since that region was smaller. Of significance was the persistent onshore transport of slope water onto the shelf, an potentially important mechanism for mixing and exchange of material between nearshore and deep water.

4.9. Geostrophic currents

Since much of our perception of the circulation in the California Current is based on geostrophic estimates of the flow, dynamic height maps determined from the CTD data are presented. The 0/500 dbar dynamic topography fields show that only May 1991 and February 1992 featured a dominant alongshore geostrophic current (Fig. 22). The seasonally strong coastal upwelling signal in spring led to the equatorward geostrophic current and low dynamic thickness observed in May. At the other extreme, the February 1992 dynamic heights imply an unusually thick dynamic upper layer, and a strong poleward flow over the slope.

The remaining three surveys display generally incoherent height fields, implicating submesoscale eddy activity. The February 1991 heights reflected poleward flow over the outer slope, albeit substantially weaker than in February 1992, and suggested an anticyclonic eddy centered near 37.6°N, 123.25°W. August dynamic heights showed relatively little range and considerable submesoscale motion. Likewise, geostrophic flow was incoherent in October. A weak cyclonic eddy was present near 37.4°N, 123.3°W.

The coherent poleward signature of the California Undercurrent dominated the geostrophic circulation patterns, implied from the 200/500 dbar dynamic thickness in August 1991 and February 1992 (Fig. 22). This field was almost uniform in February 1991, indicating a weak Undercurrent. In May and October the Undercurrent appeared over the upper slope, much weaker in October, and flowed offshore along a dynamic ridge. Whether this was more than coincidental with the presence of the upwelling jet/vortex pair seen in these two surveys is unclear, but an intriguing question.

5. Discussion

The results from six ADCP/CTD surveys of the Gulf of the Farallones during 1990–1992 reveal several features and patterns that characterize the region's circulation. Some of these are typical of the California Current in other locations, while others have not been documented previously. These include:

- a strong coherent poleward Slope Countercurrent (SCC) throughout the year,
- cross-shelf motions consistent with Ekman transport processes,
- considerable submesoscale eddy activity in several seasons,
- strong association between flow features and water types/water mass gradients,
- discrepancies between ADCP and geostrophic circulation patterns and magnitudes, and
- no clear seasonal pattern in circulation.

5.1. Slope countercurrent (SCC)

Flow along the continental slope of the Gulf of the Farallones was poleward in all seasons, with a large (1–3 Sv) transport in the upper 400 m. While the SCC displayed some vertical shear, its direction was poleward throughout the upper 300 m or more, with the strongest velocities often seen near the surface. The SCC was also highly variable from cruise to cruise in terms of its intensity, shape and location. ADCP transports are comparable in magnitude, structure and variability to those estimated from the moored current-meter measurements of this study (Noble and Ramp, 2000). Geostrophic transports across CalCOFI line 60, which runs through the Gulf, and in the CODE region immediately to the north, suggest a much weaker [O(0.1 Sv)] poleward flow in the upper 500 m (Bray and Greengrove, 1993)]. However, Bray and Greengrove (1993) found surface-enhanced poleward transports comparable to those from this study around northern California headlands, particularly Cape Mendocino, provided a 1500 dbar reference velocity level was used. Freitag and Halpern (1981) reported similar large poleward transports over the upper 900 m in this region, again from hydrographic data, although this appears to be confined to below 300 m.

The curl of the wind stress is a likely mechanism for barotropic poleward flow over the slope (Hickey, 1979). Wind climatologies (Nelson, 1977; Dorman and Winant, 1995), as well as buoy data (Fig. 2) and shipboard observations (Jessen et al., 1992a,b,d; Rago et al., 1992) from this study all suggest an enhanced, recurring, year-round positive wind-stress curl over the Farallones area, in the lee of Point Reyes. A similar spatial wind pattern has been observed around Point Conception (Nelson, 1977; Dorman and Winant, 1995; Oey, 1996; Wang, 1997) and, in summer, around Cape Blanco (Nelson, 1977).

During periods of upwelling-favorable wind, a cross-shore pressure gradient set up by offshore surface Ekman transport creates an equatorward geostrophic current. If the wind field is spatially uniform, this flow will remain balanced. However the equatorward current converges under a positive wind-stress curl, setting up a poleward pressure gradient. Eventually this pressure gradient force will overcome the geostrophic balance, creating a net poleward current. Largier et al. (1993) attributed poleward flow off northern California to a poleward pressure gradient, perhaps set up by alongshore variations in the alongshore wind stress. Model results (McCreary et al., 1987; Oey, 1996; Wang, 1997) substantiate this idea. The Countercurrent may also contain a considerable ageostrophic component due to the advection of vorticity (Oey, 1996).

Poleward flows of various strengths, positions, and depths are not unusual in the CCS (Wooster and Jones, 1970; Halpern et al., 1978; Hickey, 1979; Lynn et al., 1982). The variability, or even absence, of poleward near-surface flow in other regions of the California Current could be the result of several factors, and points to the complex relationship between the effects of wind stress and its curl, over a range of frequencies from annual to synoptic. The Farallones region, along with Point Conception and, in summer, Cape Blanco, have a coastal morphology and associated wind field that favors a persistent poleward flow.

5.2. *Cross-shelf flow*

Shelf flow was variable and coupled to local wind forcing. The cross-shelf current pattern was generally consistent with classic Ekman dynamics. This also was reflected in the surface and deep layers over the slope, although the slope flow was greatly complicated by secondary (eddy-like) circulation, as discussed below. Ekman circulation was consistent with moored current patterns (Noble and Ramp, 2000), who suggest that cross-shelf flow in the Gulf is controlled by synoptic wind stress variability.

Poleward flow and temperature on the shelf north of Point Reyes increase during wind relaxation events, but salinity changes little (Winant et al., 1987). Send et al. (1987) concluded that during relaxation events, cross-shore advection was small and northward advection of solar-heated waters was responsible for the rise in temperature. However, the Send model is not consistent with the onshore currents and fresher water seen over the slope in the Gulf of the Farallones during relaxation. Climatological maps of temperature and salinity (Lynn et al., 1982) show that the only reasonable source of warm, fresh water was from offshore. Possibly because of its geography, the Gulf experiences a very different circulation during wind relaxation events than the coastal region to the north.

We pose a different relaxation model for the Gulf. During equatorward winds, the surface Ekman layer off central California flows offshore where it mixes with the lower-salinity PSAW of the California Current. In turn, the subsurface onshore flow transports PSAW onto the slope and outer shelf. During periods of wind relaxation or reversal to poleward stress, isopycnals adjust downward. This produces a warmer and fresher signal on pressure surfaces throughout the upper 200–300 m, as PSAW flows onshore in the upper layer. This process could contribute to the mixing of this water with coastal PEW, and is likely to be enhanced around headlands (Rosenfeld et al., 1994).

5.3. Submesoscale circulation features and water mass characteristics

Submesoscale vortices, superimposed on the general circulation of most surveys, were evident in the ADCP and CTD fields. These are very reminiscent in size, strength, and water-mass character of model-generated features (Oey, 1996; Wang, 1997), and are similar to those observed repeatedly in this region (Parker, 1996; Baltz, 1997; Huyer et al., 1998). While spatial variability on this scale has been noted before in this region (Schwing et al., 1991; Rosenfeld et al., 1994), it has been missed frequently in large-scale surveys. These features do not always appear in dynamic height fields.

Water-mass characteristics associated with current features provide insight about the factors leading to the observed circulation. Areas of poleward flow coincide with relatively spicy subsurface anomalies. This close relationship implies that poleward currents transport water with a relatively high PEW content into the area, which suggests the SCC is connected with a fairly continuous poleward current.

The occurrence and position of anticyclonic eddies or meanders, and their spicy centers, indicate a slope origin. Huyer et al. (1998) suggested the eddies they observed to the west of this region in summer were generated over the continental margin. It appears that anticyclones are generated by an interaction of the spicy SCC or California Undercurrent with the area's submarine topography. The complex topography off central California can disrupt the northward flow of the Undercurrent (Robson, 1990), making this region conducive for the formation of the eddies described here. The complex wind field may be another mechanism for generating vortices in the upper ocean, such as those seen in May 1991. Conversely, cyclonic eddies and meanders were observed in each survey with a bland (high PSAW) center. They appear to have formed from California Current water, possibly through a similar mechanism to that responsible for anticyclone genesis.

Garfield et al. (1999) propose frictional torque as the dominant mechanism for the formation of a class of submesoscale (rotational radius of 15–33 km) spicy-core anticyclones, which they termed "cuddies" (California Undercurrent eddies). These are part of a larger class of circulation features known as "submesoscale coherent vortices", or SCVs. Frictional torque imparted by topography against the right-hand side of a boundary current reduces the potential vorticity of a water mass, producing anticyclonic SCVs (D'Asaro, 1988). Topography to the left of a flow will frictionally alter vorticity in a manner that generates cyclonic SCVs. However, the effect of the earth's rotation will favor the production of relatively stronger anticyclones. SCVs can develop as surface-intensified or subsurface vortices (D'Asaro, 1988).

The results of Garfield et al. (1999) also indicate the presence of cuddies throughout the year. From the velocity and spiciness fields described here, the centers of the anticyclones deepen from spring to autumn in association with the depth of the SCC. This supports the idea that poleward flowing warm, saline water is the source for these vortices. It also indicates a more general mechanism for eddy genesis beyond the cuddies, and further blurs the distinction between the California Undercurrent and the SCC.

An important implication of the region's eddy activity is the potential for these features to transport and intermingle large volumes of different water types within and near the Gulf of the Farallones. During most of the cruises, eddies and other circulation features embedded with PSAW from the California Current were found over the slope adjacent to PEW, often separated by strong temperature and salinity fronts. This mechanism for relocating shelf, slope and offshore water types is likely to be a major factor in mixing nearshore and open ocean water and material. T/S curves also imply interleaving and lateral mixing of these waters (Fig. 9).

5.4. ADCP versus geostrophic currents

The circulation derived from ADCP measurements differs from the geostrophic currents derived from the density structure. In particular, geostrophic velocities were consistently weaker than measured currents and had an equatorward bias relative to ADCP velocities. The 0/500 dbar dynamic height maps (Fig. 22) are not visually correlated with the ADCP upper ocean velocities. The geostrophic calculations do not properly reflect the poleward flow, either because this flow extended below the 500 m reference depth, or it was caused by a poleward pressure gradient. Poleward currents in the vicinity of the coast may also have an ageostrophic component, possibly generated by vorticity advected by the upwelling jet (Oey, 1996).

Historical information derived from dynamic topography is problematic. Poleward geostrophic flow in the upper 500 m off northern California is much greater when referenced to 1500 m than to 500 m (Bray and Greengrove, 1993). Current meters have detected significant poleward velocities at depths greater than 1000 m over the slope (Kinoshita et al., 1992). The correspondence between the depth of isopycnal surfaces (Ramp et al., 1997) with ADCP current features suggests a thermal wind balance may account for the current dynamics. Therefore, direct current measurements are necessary for determining the prevalence and seasonality of poleward flow. The design of many large-scale surveys may be incapable of resolving the relatively narrow SCC that lies inshore of survey stations.

5.5. Lack of seasonal circulation

There is no obvious seasonal pattern to the circulation. The SCC was seen in all six Farallones surveys, although it was least clear in May when coastal upwelling dominated. The alongshore pressure gradient, a likely candidate for driving a poleward current, is weakest in early spring and strongest in late summer (Hickey and Pola, 1983; Largier et al., 1993), roughly coinciding with the transition from a shallow SCC early in the year to a deeper SCC core in August. Monthly and seasonal climatologies of geostrophic velocities off California suggest that poleward flow is weak or absent in the spring (Wyllie, 1966; Pavlova, 1966; Chelton, 1984; Lynn and Simpson, 1987; Tisch et al., 1992), yet current meter time series show that spring is the season of maximum poleward flow (Wickham et al., 1987; Collins et al., 1996; Huyer et al., 1989).

Strub et al. (1987) state that coastal current variance off central California "cannot be accounted for by the annual cycles". Only 20% of geostrophic current variance off northern California is due to seasonal fluctuations, versus 50% by interannual (Bray and Greengrove, 1993). Moored current meter time series taken during our project (Noble and Ramp, 2000) have no clear seasonal cycle either. Certainly large-scale pressure, wind, insolation, and sea-level fields have a distinct annual cycle (cf. Strub et al., 1987). While there is probably some effect of seasonal atmospheric and basin-scale ocean fluctuations on flow in the Gulf of the Farallones, we suggest that large-scale seasonal variations in forcing interact with synoptic wind forcing and the region's topography and orography to produce a complex mesoscale circulation that dwarfs any seasonal signal.

5.6. Interannual variability

The August 1990 and 1991 cruises, while featuring different survey plans, displayed a similar circulation pattern. The two February surveys show greater interannual variability. Changes in the Gulf in February 1992 have been attributed partly to the 1992–93 El Niño. Sea-level measurements and output from a global circulation model suggest a coastal Kelvin wave triggered in the tropics passed through the Gulf at the same time as the February cruise (Ramp et al., 1997). This wave was seen in dynamic height fields from nearby surveys in this time frame (Lynn et al., 1995).

ADCP flow over the slope was strongly poleward in February of both years, but the strongest velocities were more concentrated into the upper 100 m in 1992 (Figs. 6 and 18). The SCC was very evident in surface geostrophic velocities (Fig. 22). Flow was strongly shoreward and the Gulf was warmer and fresher compared to 1991. In essence, the California Current was displaced onshore. Adjustments in the density field in the upper 300 m were balanced by a strongly baroclinic geostrophic poleward flow in the upper 150–200 m. In addition, stronger poleward transport during early 1992 may have been responsible for bringing a higher percentage of PEW into the region, a tendency seen by Lynn et al. (1995). Historically, interannual variations in coastal sea-level, surface temperature, and salinity in the CCS have been positively correlated and relatively higher in El Niño years (Chelton et al., 1982), implying a reduced net equatorward transport during El Niños and leading to a northward displacement of PEW. As with the seasonal signal, however, it is very difficult to separate interannual differences between surveys from variability due to processes occurring on shorter time scales.

5.7. Applications to the disposal of dredge spoils

Material dredged from San Francisco Bay to maintain safe navigation is transported offshore in barges and dumped at a site over the continental slope off the Gulf of the Farallones. It is undesirable for currents to carry the dredged materials back onshore and into the federally protected waters of the Gulf of the Farallones National Marine Sanctuary and the Monterey Bay National Marine Sanctuary. Persistent poleward slope flow over much of the water column suggests northward transport of material is very likely. Given the seeming lack of a strong annual cycle in circulation, there is no seasonal preference to scheduling dumping activity. However, material dumped over the slope during wind relaxation or reversal events, which occur throughout the year, is likely to be returned onshore while in the surface layer. The region also appears to be a site of eddy genesis, which could retain dredge material or eventually move it offshore. On the other hand, the various processes forcing the region's circulation contribute to enhanced mixing between coastal and offshore waters. In particular, the frequent meanders and eddies in the circulation are associated with specific water types, and exhibit a capability for moving large volumes of slope and offshore water. While the results from these surveys are limited in their ability to define persistence in submesoscale circulation features on a scale similar to that of the dump site, other studies of ADCP, CTD, and AVHRR data from this area indicate that the eddies and jets observed during these cruises are closely tied to geographic features and sites (Parker, 1996; Baltz, 1997).

6. Summary

To summarize the region's circulation, southward-blowing winds cause offshore Ekman transport of the surface layer, and upwelling of cool, salty (yet relatively spicy) water near the coast. Onshore Ekman transport at depth brings PSAW toward the outer shelf. Lowered coastal sea-level results in an equatorward geostrophic flow. Associated with the relatively steady equatorward stress is a persistent positive wind-stress curl, enhanced by the local coastal orography. In time, a curl-induced barotropic poleward flow overcomes equatorward geostrophic transport. The result is a persistent, relatively barotropic poleward current over the continental slope, which transports PEW northward along the slope adjacent to the Farallones. The elements of this circulation are summarized in Fig. 23.

A number of processes can alter the two-dimensional circulation, bringing fresher PSAW onshore and into the Gulf. These include periodic wind relaxation or reversal events, shifts in the wind-stress curl field, steering effects from local orographic or bathymetric features, offshore transport by coastal upwelling jets, and onshore transport by meanders in the California Current due to flow instabilities. They also may be linked to perturbations in the California Undercurrent (Noble and Ramp, 2000). Like upwelling, these intrusions are not uniform alongshore but have preferred areas of onshore movement. They may have a rotation imparted by shear from upwelling jets or current instabilities. Their movement shifts the balance of the density field, forcing

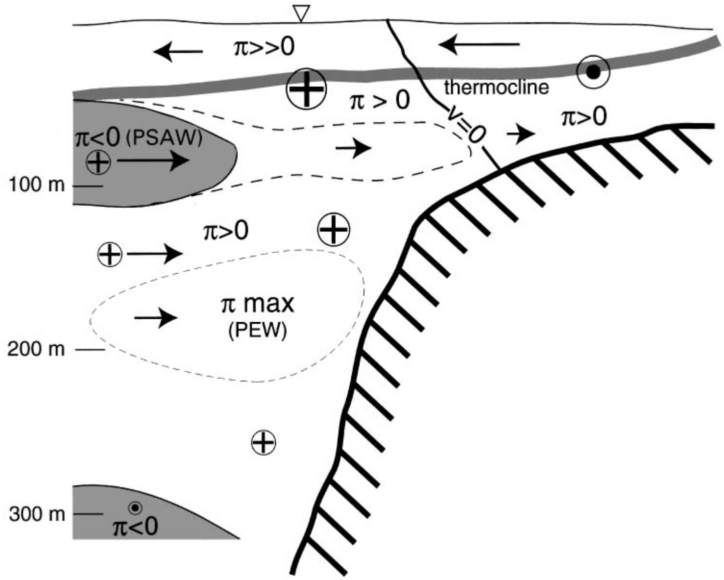

Fig. 23. Conceptual model of the idealized cross-shelf distribution of water mass characteristics and flow. Circle with a center dit (cross) indicates equatorward (poleward) flow. Size of circle represents the relative magnitude of flow. Typical position of zero alongshore isotach over outer shelf noted. Cross-shelf velocity components correspond to size of arrows. Magnitude of spiciness anomaly (π) shown for different regions, with negative spiciness (bland water) shaded. Dashed lines indicates episodic onshore transport of PSAW during wind relaxation events. Thick gray line denotes approximate position of thermocline.

geostrophic adjustments to the circulation that create or reinforce eddy-like flow features. We speculate that the periodic onshore movement of PSAW into the region leads to submesoscale mixing, which dilutes PEW carried by poleward flow. This may be a mechanism that enhances the exchange between these water types, as well as between coastal and offshore regions (and their flora and fauna).

The circulation in the Gulf of the Farallones region is the sum of (i) a strong, persistent, large-scale barotropic poleward slope flow, (ii) mesoscale Ekman circulation set up by local wind forcing that fluctuates on synoptic time scales, (iii) eddy development associated with the Point Reyes upwelling jet, and (iv) baroclinic adjustments in response to a changing density field that is the interplay of PSAW and PEW, generated by submesoscale instabilities in large-scale boundary currents interacting with topography. The relative quantity of PEW over the slope gradually declines with distance north in the California Current (Blanton and Pattullo, 1970; Lynn et al., 1982). This has been explained as gradual mixing of PEW carried by the Undercurrent, or in this case the SCC, with PSAW in the California Current. However, the periodic cross-shelf exchange of PSAW and PEW due to episodic wind events and submesoscale circulation features may enhance mixing locally. Because of the very dynamic three-dimensional nature of the Gulf of the Farallones' regional circulation, this is likely to be a center for active mixing and exchange between the coastal and California Current waters, relative to most US west coast locales.

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