Title

Density driven headland retention in a strong upwelling system: Implications for larval transport

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Publication Date

2005

Peer reviewed

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 110, C10027, doi:10.1029/2005JC002898, 2005

Subsurface recirculation and larval retention in the lee of a small headland: A variation on the upwelling shadow theme

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Received 29 January 2005; revised 22 April 2005; accepted 24 June 2005; published 27 October 2005.

[1] The interaction of alongshore coastal currents with large headlands has been shown to increase the retention of planktonic organisms through the formation of headland eddies or upwelling shadows in their lee. This study investigates the circulation within Bodega Bay (in the lee of a small headland), in an upwelling region, and the potential for retention of plankton. During the upwelling season of 2004, time series of temperature and velocity were recorded throughout Bodega Bay, conductivity-temperature-depth (CTD) surveys were conducted, and surface drifters were released during upwelling, downwelling, and relaxation conditions. Postlarval settlement was monitored daily over two periods coinciding with CTD surveys. Under strong upwelling favorable conditions, wind-driven surface currents were equatorward both offshore and throughout the bay. However, there was significant current shear along the eastern shore of the bay where cold bottom waters move poleward, counter to the direction of the wind-driven surface flow. During downwelling and relaxation conditions, flow was poleward throughout the water column along the eastern shore of the bay. Postlarvae settled during all wind conditions, but greatest settlement was observed at the onset of upwelling favorable conditions. While no “typical” upwelling shadow is evident in the lee of the Bodega headland, subsurface recirculation driven by the alongshore flow past Bodega Head may facilitate the retention of plankton in the bay. Previous studies have generally focused on large headlands; however, it is likely that other small embayments in the lee of small headlands may also provide retention opportunities for planktonic organisms in upwelling regions.

Citation: Roughan, M., A. J. Mace, J. L. Largier, S. G. Morgan, J. L. Fisher, and M. L. Carter (2005), Subsurface recirculation and larval retention in the lee of a small headland: A variation on the upwelling shadow theme, *J. Geophys. Res.*, *110*, C10027, doi:10.1029/2005JC002898.

1. Introduction

[2] In recent years, substantial progress has been made in understanding wind-driven dynamical processes in coastal upwelling systems. Specifically, observations from the Coastal Ocean Dynamics Experiment (CODE) [*Kosro and Huyer*, 1986; *Huyer and Kosro*, 1987; *Kosro*, 1987; *Winant et al.*, 1987], the Northern California Coastal Circulation Study (NCCCS) [*Largier et al.*, 1993] and the Surface Mixed Layer Experiment (SMILE) [*Dever*, 1997] highlight the spatial and temporal variability of wind forcing in the northern California region and the associated upwelling response. This work has been continued by *Wing et al.* [1995a, 1995b, 1998] and the Wind Exchange Shelf Transport (WEST) program (J. L. Largier et al., WEST: A northern California study of the role of wind-driven transport in the productivity of coastal plankton communities, submitted to *Deep-Sea Research, Part II*, 2005, hereinafter referred to as Largier et al., submitted manuscript, 2005) which aimed to link physical oceanographic processes with the response of plankton communities in the region between Pt. Reyes (38°N) and Pt. Arena (39°N) on the west coast of the United States (Figure 1). Still poorly known, however, is the influence of coastal topographic form on physical and biological processes (e.g., meroplanktonic dispersal), in particular the effect of headlands and associated bays on the structure of coastal flows.

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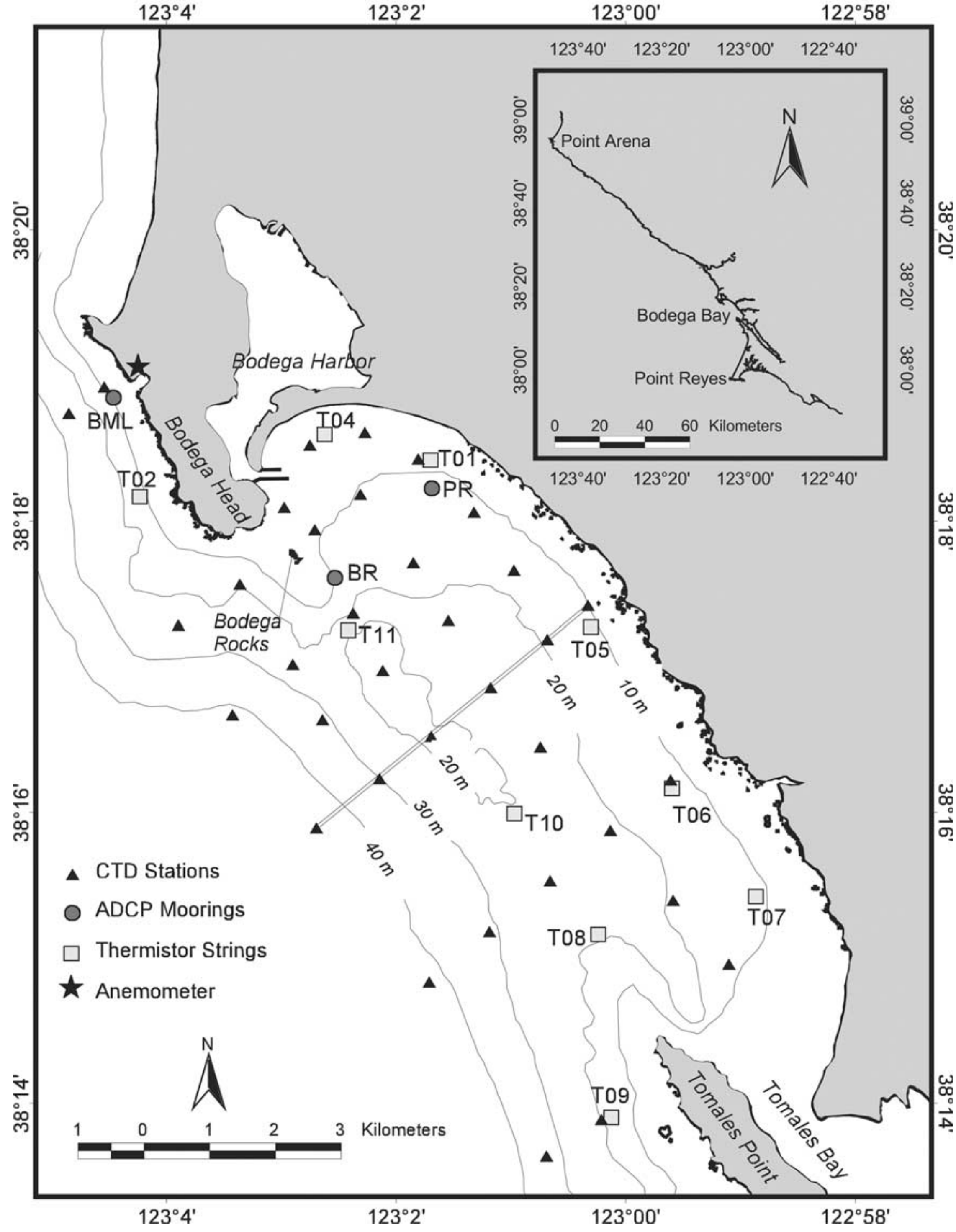

Figure 1. Map showing the location of the 30 CTD stations (triangles), 3 ADCP moorings (circles), and 10 thermistor strings (squares). The shore-normal line at T05 line represents a CTD transect within Bodega Bay, and the thin black lines are the bathymetric contours. The inset shows the location of Bodega Bay north of Pt. Reyes on the west coast of the United States.

[3] Headlands and capes can play a dominant role in causing alongshore variability of upwelling driven coastal flow [*Gan and Allen*, 2002a, 2002b], but the in-bay processes are poorly understood. Furthermore, the physical mechanisms responsible for biological patterns are often deduced with little direct observation of transport and forcing. For example, it has been suggested that the interaction of alongshore coastal currents with headlands would increase offshore transport and thus negatively affect the recruitment of meroplanktonic populations [*Ebert and*

Russell, 1988]. However, several studies have observed increased zooplankton abundance in headland-generated oceanographic features such as fronts and eddies [*Caffey*, 1985; *Murdoch*, 1989; *Rankin et al.*, 1994; *Graham and Largier*, 1997; *Wing et al.*, 1998]. Additionally, some studies have reported higher larval settlement patterns in headland associated embayments compared to surrounding areas, suggesting that bays can act as retention zones [*Gaines and Bertness*, 1992; *Wing et al.*, 1995a; *Archambault and Bourget*, 1999; *Lagos et al.*, 2002]; however, few of these studies [*Wing et al.*, 1995a; *Lagos et al.*, 2002] were conducted in upwelling systems. For example, *Wing et al.* [1995a] found evidence of limited larval dispersal even in areas of intense upwelling, despite extensive offshore transport of water, suggesting local retention mechanisms on a scale of approximately 100 km. Thus marine populations in wind-driven upwelling regions may not be as open as once thought [*Sponaugle et al.*, 2002; *Strathmann et al.*, 2002; *Swearer et al.*, 2002]. A better understanding of flow around headlands and in bays (particularly on a small scale) may resolve the apparent contradiction between *Ebert and Russell*'s [1988] view of weaker settlement and *Wing et al.*'s [1995a] view of stronger settlement associated with headlands.

[4] In this study "retention" is used to describe a region where plankton are subject to reduced dispersion. In particular, for the propagules of coastal benthic populations this may be important in two ways: (1) Reduced offshore dispersion may increase the probability of being nearshore when competent to settle, and (2) reduced alongshore dispersion may increase local recruitment. Multiple mechanisms may be responsible for the retention of zooplankton in embayments associated with headlands. In particular, residence in bays may be promoted by frontal zones at the mouth of bays [*Graham et al.*, 1992; *O'Donnell*, 1993; *Wing et al.*, 1998; *McCulloch and Shanks*, 2003; *Shanks et al.*, 2003; *Miller and Shanks*, 2004], recirculation features [*Murdoch*, 1989; *Chen et al.*, 1997; *Graham and Largier*, 1997], and through vertical migratory behavior in the presence of vertical shear [*Peterson et al.*, 1979]. Furthermore, warmer water and elevated concentrations of food in embayments may speed development, thereby reducing the pelagic larval duration and exposure to pelagic predators [*Castilla et al.*, 2002; *Lagos et al.*, 2002; *Largier*, 2004]. Physical evidence for increased residence time of water in an embayment may consist of warmer water in the bay than along the adjacent exposed coast, a lag between change of water temperature inside and outside the bay, increased water column stratification in the bay, or a reversal of current direction from the predominant flow. These circulation features may be due to tides, wind, offshore currents, and buoyancy, and because tidal and wind influences are variable, circulation features and zooplankton retention are likely to be spatially and temporally transient.

[5] Previous interdisciplinary studies of headland dynamics and biological interactions have typically been conducted on scales ranging from 10 to 100 km [*Murdoch*, 1989; *Rankin et al.*, 1994; *Graham and Largier*, 1997; *Wing et al.*, 1998]. Although studies of headland dynamics have been conducted on smaller scales [e.g., *Geyer and Signell*, 1990; *Signell and Geyer*, 1991; *Edwards et al.*, 2004; *Roughan et al.*, 2005], few studies have investigated the dynamics driving the biological response on scales less than 10 km. Addressing whether similar mechanisms operate at smaller scales is important for understanding local marine community dynamics and for siting marine reserves, which typically have alongshore scales less than 10 km. Thus the goals of this study are (1) to describe and explain flow patterns within Bodega Bay, (2) to relate these flow patterns to the concept of an "upwelling shadow" and the potential for larval retention in Bodega Bay, and (3) to interpret postlarval crab settlement in terms of these flow patterns.

2. Methods

2.1. Study Area

[6] This study was conducted during the 2004 upwelling season in the region of Bodega Bay, California (Figure 1). Typically, the spring and summer months (May–July), are characterized by persistent equatorward (upwelling favorable) winds in this region. A previous review of Bodega Bay circulation [*Shenker*, 1989] suggested the dynamics are complex and highly variable over short temporal and spatial scales and are influenced by winds, tides, and local and regional topography. Bodega Bay is a shallow broad southwest facing embayment located in the lee of Bodega Head (38°18′N, 123°04′W). The mouth of the bay is approximately 11 km from the northern tip (Bodega Head) to the southern tip (Tomales Point), expanding to 15 km wide landward of the mouth, and is approximately 3.5 km from mouth to shore. The rocky outcrops of Bodega Head and Tomales Point continue as a shallow (<15 m) submarine ridge across the mouth of the bay. At the northern end of the bay, this ridge rises to the surface to form Bodega Rocks, and offshore of the ridge, depths increase quickly to 40 m or more. Onshore of the ridge, depths of 20–25 m are observed, creating a deeper, more enclosed bay. Deep, narrow passages lead through the ridge immediately south of Bodega Rocks (~$^1/_2$ km wide and 20 m deep) and at the southern end of the bay (2 $^1/_2$ km wide, 25 m deep). The semienclosed waters of Bodega Harbor and Tomales Bay (to the north and south, respectively) connect directly to Bodega Bay, more than doubling the surface area. Tides in the bay are mixed semidiurnal with a tidal range of 1.2–2.9 m. Strong tidal currents at the mouth of Bodega Harbor extend as a tidal jet up to 2 km into Bodega Bay [*Rasmussen et al.*, 2004]. The bay is also influenced by the tidal outflow from Tomales Bay and mixing with offshore waters and from winter freshwater influx from Tomales Bay and two small creeks that enter Bodega Bay.

2.2. Data

[7] The field data collected during this study include (1) time series observations of wind speed and direction, current velocity profiles, and temperature throughout the water column; (2) spatial hydrographic surveys from a small boat; (3) measurements of surface velocities with Lagrangian drifters inside Bodega Bay; and (4) settlement of postlarval crabs.

2.2.1. Wind

[8] Offshore wind speed and direction were obtained from an automatic weather station at the offshore site NDBC 46013 (38° 13.30N, 123° 19.00W; http://www.ndbc.noaa.gov/) and local wind velocities were obtained from a land-

Table 1. Details of ADCP and Thermistor Deployment, May to July 2004[a]

Instrument Type	Mooring	Date Deployed	Record Length, days	Latitude, °N	Longitude, °W	Water Depth, m
ADCP	PR	19 May	49	38 18.3612	123 1.6800	12.2
ADCP	BML	21 May	33	38 18.8478	123 4.4598	11.6
ADCP	BR	21 May	33	38 17.6070	123 2.5308	13.1
Temperature	T1	20 May	73	38 18.4150	123 1.7030	13.7
Temperature	T2	20 May	73	38 18.1640	123 4.2360	13.7
Temperature	T4	20 May	73	38 18.5920	123 2.6260	7.6
Temperature	T5	20 May	73	38 17.2699	123 0.3060	16.8
Temperature	T6	20 May	73	38 16.1639	122 59.6000	13.7
Temperature	T7	20 May	73	38 15.4199	122 58.8700	13.7
Temperature	T8	20 May	31[b]	38 15.1580	123 0.2400	21.3
Temperature	T9	20 May	31[b]	38 13.9000	123 0.1290	15.2
Temperature	T10	20 May	73	38 15.9890	123 0.9710	24.4
Temperature	T11	20 May	31[b]	38 17.2490	123 2.4190	18.3

[a] Latitude and longitude are in WGS 84. Three Optic StowAway TidbiT® thermistors were located on each temperature mooring: 1 m off the bottom, mid water column, and 1 m below the surface. Temperature ±0.2°C was recorded every 2 min.

[b] Value denotes short record length because moorings were lost.

based site at the Bodega Marine Laboratory (http://bml.ucdavis.edu/boon/). The 10 min averaged data were adjusted to a height of 10 m above sea level using a neutral stability wind profile, decimated to hourly data, and rotated to a principal axis of 320°T and 305°T (NDBC 46013 and BML, respectively).

2.2.2. Current Profiles

[9] Time series of current velocity and direction were obtained using bottom-mounted RDI 1200 kHz acoustic Doppler current profilers (ADCPs) at three nearshore locations: (1) off Bodega Marine Laboratory (BML) on the open coast west of Bodega Head and north of Bodega Bay, (2) on the inshore southeastern edge of Bodega Rock (BR) in the lee of Bodega Head, and (3) off Pinnacle Rock (PR) along the eastern shore of northern Bodega Bay (Figure 1). The BML site was chosen to represent alongshore flow upstream of the mouth of the bay while the BR and PR sites were selected to be at each side of the entrance to the northern subembayment formed by Bodega Rocks. The ADCPs were deployed at a depth of 11.5 m, 13 m, and 12 m (BML, BR, and PR, respectively) for periods of 33 (BML and BR) and 49 days (PR) (Table 1). Post processing included averaging the 3 min ensemble velocities to either 15 min or hourly and rotating magnetic compass directions to true north. The principal axis of each velocity time series was calculated from the subtidal depth averaged velocity at each mooring and was found to be −30°, −3°, and −8° at BML, BR, and PR respectively. Velocity records at each mooring were rotated through the respective principal axis such that positive alongshore flow (v) is in the y direction (poleward) and positive across-shore flow (u) is in the x direction (onshore). Because the tidal range is 25% of the maximum instrument depth, all current velocities are reported in 1 m bins at a depth above the bottom rather than depth below the surface.

2.2.3. Temperature

[10] Ten thermistor moorings were deployed throughout the bay for the period 20 May to 1 August 2004 (Figure 1). Most of the moorings were in approximately 15 m of water (Table 1). Three Optic StowAway TidbiT® thermistors (which recorded temperature (T ± 0.2°C) every 2 min) were placed on each mooring: 1 m off the bottom, (∼14 m), mid water column (∼8 m) and 1 m below the surface.

2.2.4. Hydrography

[11] Spatial patterns in the hydrography and stratification of Bodega Bay were characterized using data from boat-based conductivity-temperature-depth (CTD) surveys. On each survey, vertical CTD casts were taken at 30 locations throughout the bay (Figure 1), using a Sea-bird SBE19-plus profiling CTD with a submersible pump (SBE 5T), an irradiance meter (Li-Cor PAR Sensor, model Li-193SA), a WETLabs WETStar fluorometer, and a WETLabs transmissometer. Four surveys were conducted during June and July 2004, each under a different wind regime (Table 2): 3 June (well-developed upwelling); 19 June (active downwelling); 7 July (relaxation from upwelling) and 11 July (incipient upwelling).

2.2.5. Lagrangian Drifters

[12] Pacific Gyre Lagrangian drifters were used to characterize the surface velocity field during different wind regimes. The drifters have a tristar drogue that tracks near-surface waters (<2 m). Positions were fixed every 10 min by GPS, and transmitted via a cellular phone network, allowing data to be downloaded in near real time. As many as 10 drifters were deployed for periods of up to 8 hours under the four wind regimes outlined in Table 2.

2.2.6. Postlarvae

[13] Postlarvae were collected during periods of two different oceanographic conditions coincident with CTD surveys: 31 May to 5 June (upwelling) and 14–21 June (downwelling). Three moorings were placed 50 m apart along the 10 m isobath adjacent to the ADCP mooring off Pinnacle Rock (PR). A mesh collector bag (10 × 30 cm) containing three Tuffy® kitchen scrub pads was attached to each mooring both at the surface and 1 m above the bottom. Collectors were retrieved and replaced at 24 hour intervals. Postlarvae were counted and identified to the lowest possi-

Table 2. Wind Forcing, Dates, Wind Strength, Stage, and Range of the Tide During Each of the Four CTD Surveys

	Date	Wind Strength, $\mathrm{m\ s^{-1}}$	Stage	Range, m
Developed upwelling	3 June 2004	NW 10–15	flood tide	1.5
Downwelling	19 June 2004	S 6–12	flood tide	0.9
Relaxation	7 July 2004	variable <3	slack tide	1
Incipient upwelling	11 July 2004	NW 8–12	weak ebb	0.5

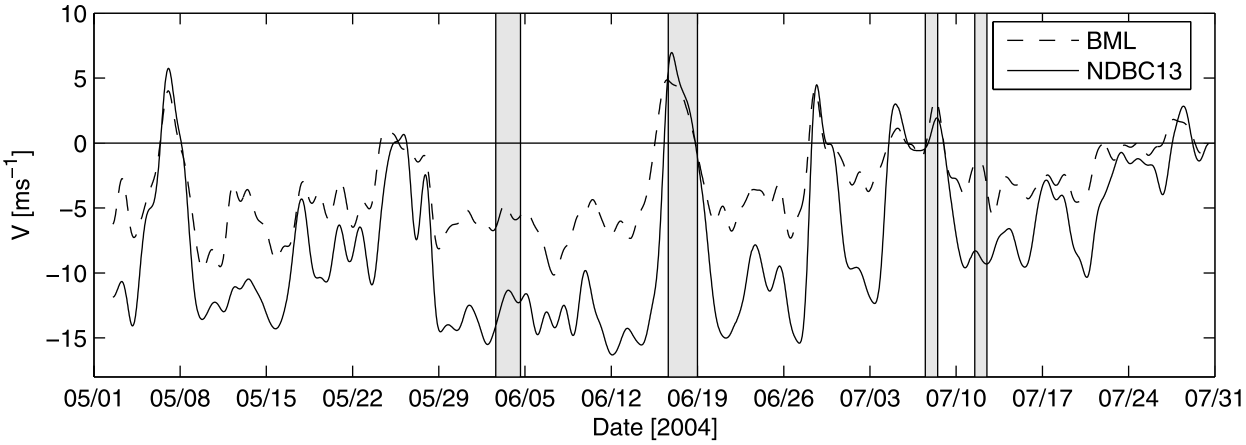

Figure 2. Time series of alongshore wind (m s^{-1}) at BML (dashed line) and NDBC 46013 (solid line). The gray bars represent the four survey periods: upwelling, downwelling, relaxation, and incipient upwelling.

ble taxa. A two-factor analysis of variance was used to determine the effect of oceanographic condition (upwelling and downwelling winds) and taxa on postlarval density (surface and bottom settlement were combined for the analysis).

3. Results and Discussion

[14] During spring and summer, the Bodega Bay region is characterized by upwelling winds with brief periods of weaker wind. Largier et al. (submitted manuscript, 2005) used 36-hour low-pass-filtered wind strength at NDBC 46013 as an index of wind conditions in the region, identifying upwelling periods as times when equatorward winds exceed 5 m s^{-1} and relaxation events as times when winds are less than 3 m s^{-1}. Downwelling can similarly be identified as periods when poleward winds exceed 5 m s^{-1}. All three stages of wind forcing were observed during the study period (marked in Figure 2). While wind events were coherent between offshore (NDBC 46013) and inshore (BML) on all occasions (95% confidence, correlation coefficient = 0.8849), offshore winds were notably stronger during upwelling events (Figure 2), suggesting that the bay and nearshore waters are sheltered from the full strength of the equatorward winds. Generally, alongshore winds at BML precede those at NDBC 46013 (lag of 2 hours) primarily because of wind relaxations occurring earlier at BML (Figure 2). This difference in speed reflects the complex spatial patterns of wind forcing in this region [*Koracin et al.*, 2004; *Dorman et al.*, 2005].

[15] Water temperatures throughout the bay fluctuate in response to synoptic scale wind forcing. Periods of cold water were observed 29 May to 16 June, 22–28 June, 3–4 July, and 13–21 July, corresponding to periods of wind-driven upwelling on the open coast (e.g., T02 in Figure 3). Warm water periods were observed during relaxation and downwelling conditions between upwelling events. Warmest waters were found following prolonged relaxation of upwelling conditions (e.g., 9–12 and 26–31 July). Maximum surface temperatures were about 15°C at these times, while minimum temperatures were about 8.5°C during strong upwelling (Figures 3 and 4). The temperature time series show there was a distinct and coherent spatial pattern in stratification and water temperatures in the bay. Stronger stratification and warmer surface waters were observed in the southern bay (T06, T07, and T08) and at stations immediately outside the southern bay (T09). The northern bay (T01 and T04) and the open coastal waters (T02, T11) were characterized by cooler waters and weaker stratification.

[16] Temperature also exhibits high-frequency variability associated with tides and diurnal forcing (Figures 3 and 4), resulting in high-frequency changes in thermal stratification. At sites near the mouth of Tomales Bay (notably T07), strong tidal (semidiurnal) temperature variability is observed at depth (e.g., T07 in Figure 5, 13–14 July, 4°C change at depth), consistent with tidal outflow of warm water from Tomales Bay [*Largier et al.*, 1997]. In the surface waters at other sites, diurnal variability is more distinct (e.g., T01 in Figure 5, 13–14 July, 3.5°C change at the surface). During periods of increased stratification, this diurnal variability is most notable at sites along the eastern shore (T01, T05, and T06) and it is likely due to diurnal surface warming.

[17] Wind forcing may be important not only in offshore transport of warm surface waters and upwelling of cold deeper waters, but also in vertical mixing. For example, at T06 and nearby thermistor strings on 12–13 June it appears that the cooling of surface waters was accompanied by the warming of bottom waters, suggesting vertical mixing at these sites. Weak diurnal variability is also observed when the water column is mixed, which is likely due to diurnal tidal effects and diurnal surface warming.

[18] Currents in Bodega Bay also exhibit a strong response to both wind and tidal forcing. The time series of current velocities are shown in the alongshore and across-shore directions at each of the three moorings (Figures 6 and 7). Wind is also plotted to delineate periods of upwelling, downwelling, and relaxation. Currents were predominantly alongshore, equatorward during upwelling periods and poleward during relaxation or downwelling periods. High-frequency fluctuations in velocity, resulting from tidal forcing, are evident in the ADCP time series shown as banding in Figures 6 and 7 (unfiltered data)

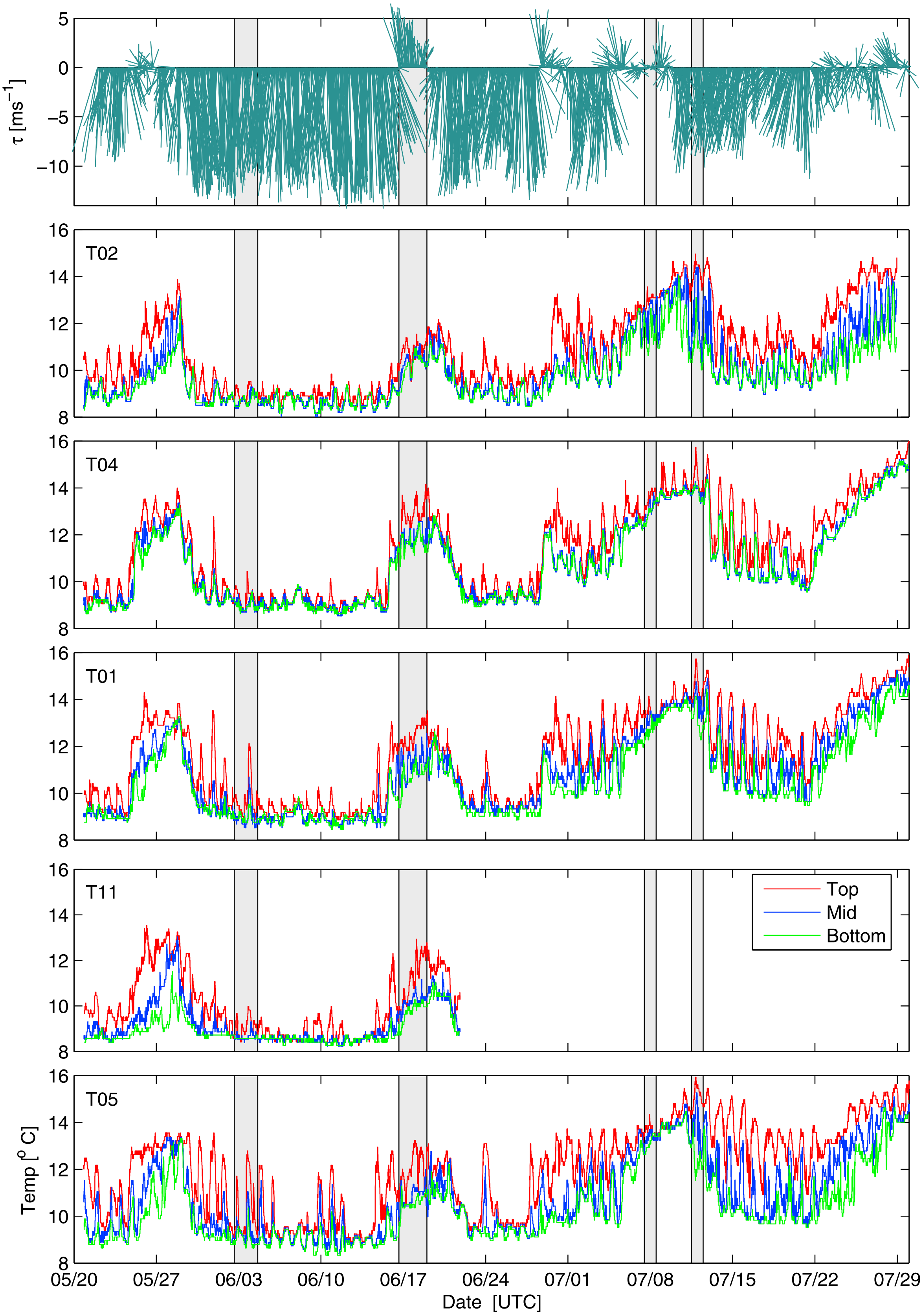

Figure 3. (top to bottom) Hourly vectors of wind velocity (m s^{-1}) from NDBC 46013, where positive values are alongshore poleward, and time series of temperature (°C) in the northern half of Bodega Bay at three depths: 1 m off the bottom (approximately 14 m), mid water column (approximately 8 m), and 1 m below the surface. Shaded areas represent the timing of the four hydrographic surveys.

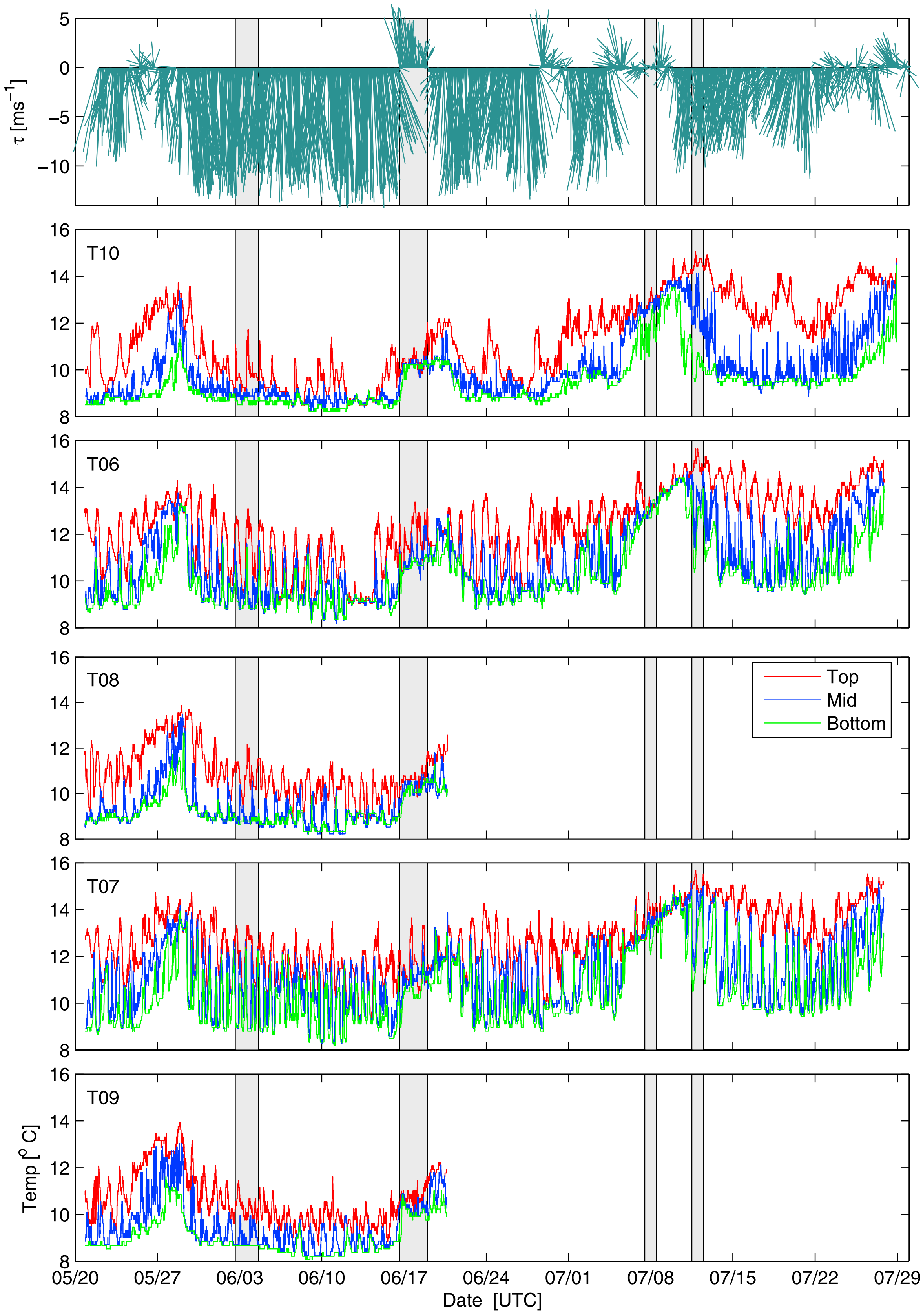

Figure 4. As in Figure 3 but for the thermistors in the southern half of Bodega Bay.

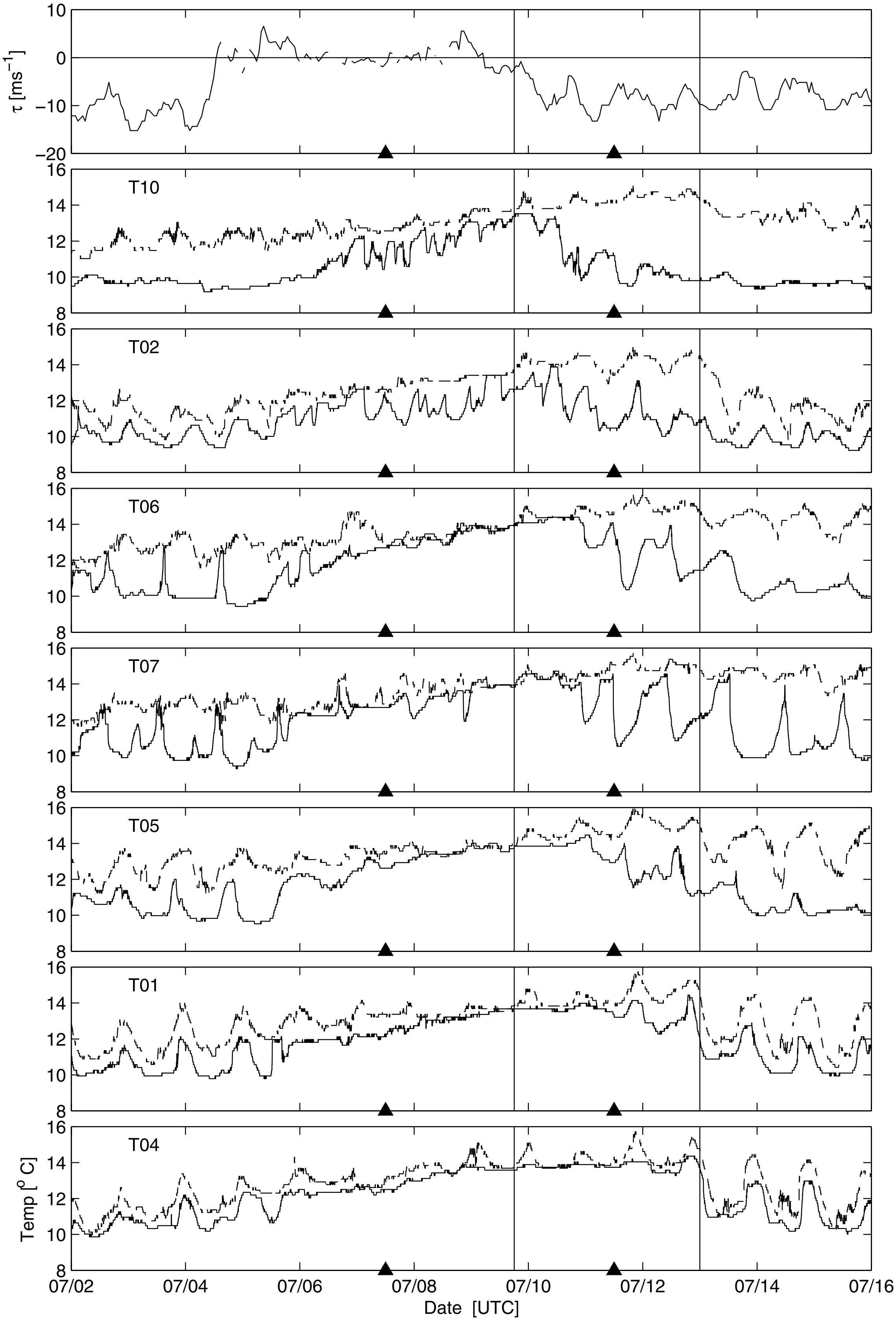

Figure 5. (top to bottom) Alongshore component of wind velocity (m s^{-1}) and temperature time series (°C) at each of the thermistor moorings subsurface (dashed lines) and at the bottom (solid lines). The vertical lines delineate the timing of an upwelling event and the associated cooling of bottom waters. The triangles represent the timing of the hydrographic surveys.

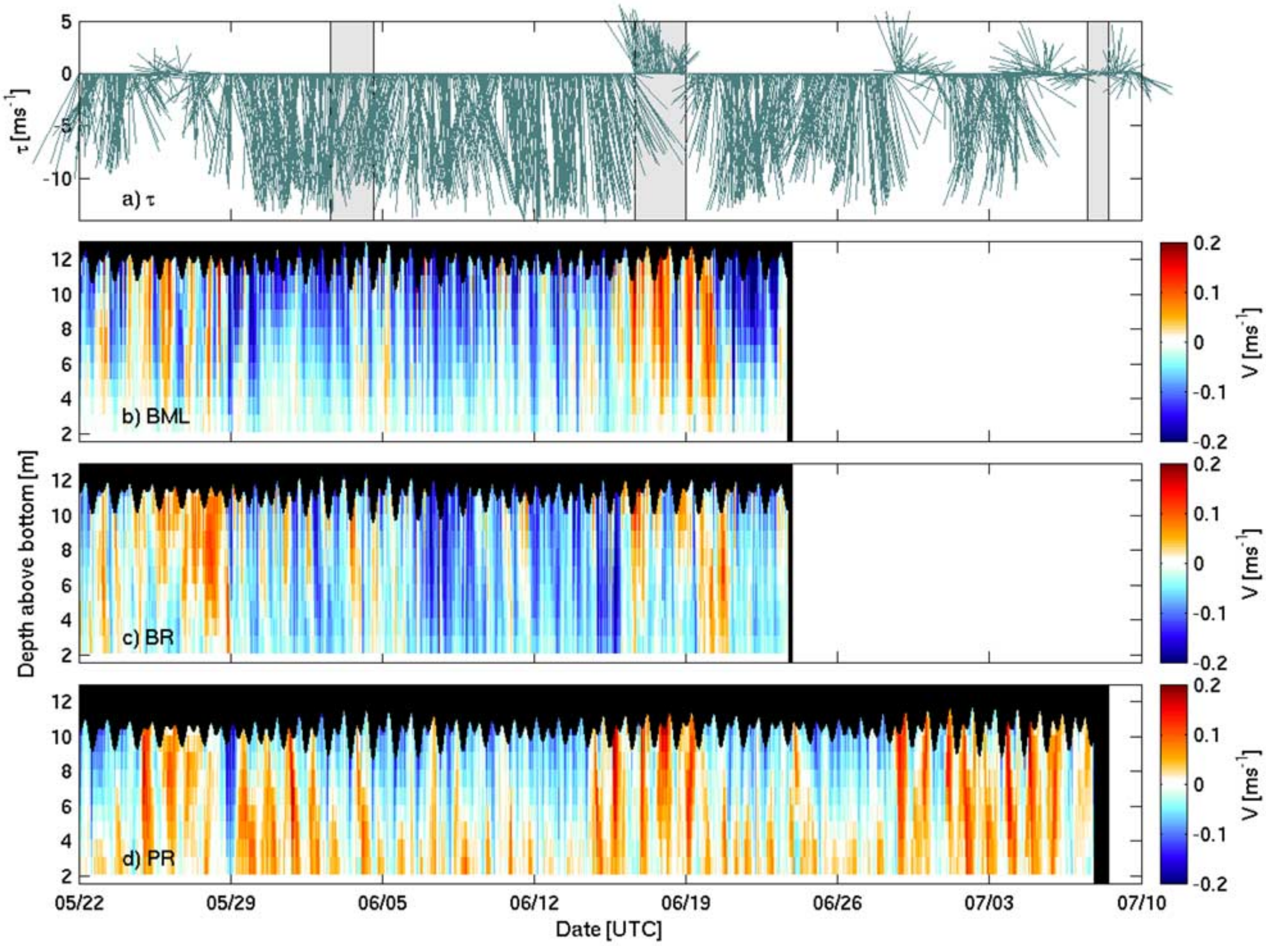

Figure 6. Time series of (a) wind (m s^{-1}) at NDBC 46013 and of alongshore current (m s^{-1}) at (b) Bodega Marine Lab (BML), (c) Bodega Rock (BR), and (d) Pinnacle Rock (PR). For the wind time series, positive velocities are directed poleward in the alongshore direction. For the current plots, the *y* axis represents distance above the bottom, and the black shading represents the sea surface elevation obtained from the pressure recorded by the bottom-mounted ADCP.

consistent with tidal fluctuations in sea level elevation (pressure).

3.1. Circulation During Upwelling

[19] During upwelling conditions, Bodega Bay is subject to at least four co-occurring forcing phenomena: (1) strong equatorward flow past the mouth of the bay, (2) alongshore pressure gradients due to alongshore variations in wind forcing, (3) wind stress on the surface of the bay, and (4) the presence of dense upwelled waters at the mouth of the bay. These forcing mechanisms interact with coastal topography, bottom stress, and tidal forcing to determine both the circulation within the bay and exchange between the bay and the shelf.

[20] During the main upwelling event (28 May to 15 June), current velocities at the BML site were strongly equatorward and slightly onshore with a near-surface maximum of 0.25 m s^{-1} decreasing to less than 0.05 m s^{-1} near bottom (Figure 6). Currents at the BR site were remarkably coherent with currents along the open coast (BML), with only a slight weakening (Figure 6). Currents at the PR site were also correlated with wind forcing, but strong vertical shear was evident. While near-surface velocities (9–11 m above bottom) were up to 0.1 m s^{-1} equatorward, near-bottom velocities (2–5 m above bottom) were up to 0.1 m s^{-1} poleward (Figure 6). The depth of zero velocity fluctuates from 7 to 9 m above the bottom, which coincided with the approximate depth of the thermocline at the base of the surface mixed layer. A similar pattern of sheared alongshore flow was seen at PR during the second upwelling event in late June evident in Figure 8.

[21] Under upwelling conditions temperature was well mixed offshore and in the outer bay (<10°C). However, warmer water (11–12°C) and stratification was observed along the eastern shore (Figure 9, first column). Salinity was high (33.8 psu) and homogeneous, indicating that the bay was filled with upwelled waters, some of which had warmed while in the bay (density 26–26.2 kg m^{-3}). Turbidity increased slightly near the entrances to Bodega Harbor and Tomales Bay. The cool isothermal waters were also evident at northern thermistor sites (Figures 3 and 4), and during strongest winds 12–15 June, the entire bay was cold isothermal at all sites except those subject to Tomales Bay outflow.

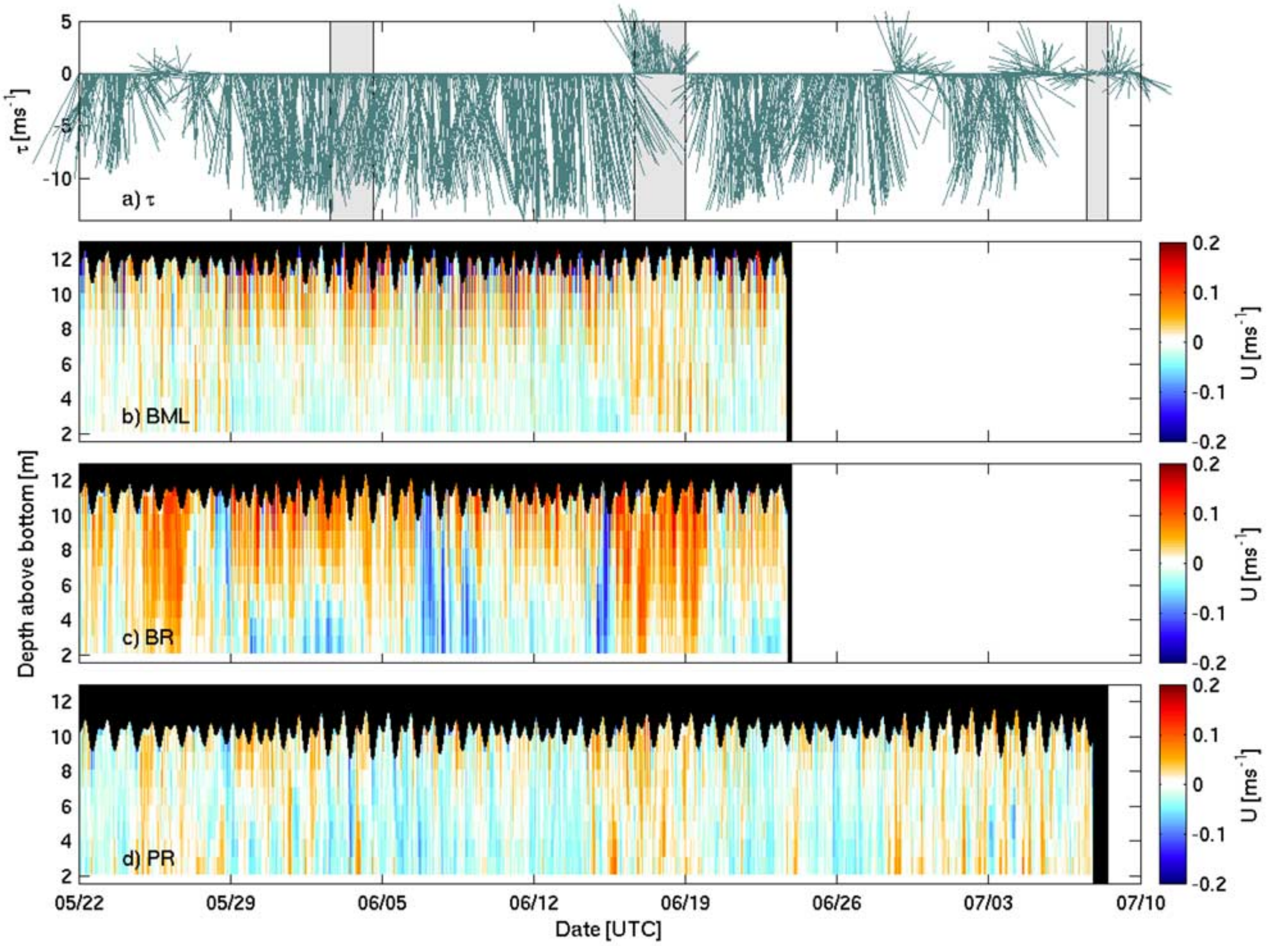

Figure 7. As in Figure 6, but the current velocities are in the across-shore direction.

[22] Strong equatorward flow past Bodega Head was recorded by the ADCP moored at BML. This site is within a coastal boundary shear zone and flow further offshore is significantly stronger [*Kaplan and Largier*, 2005]. The bulk of this equatorward flow can be expected to separate from the coast at the southern end of Bodega Head and run along the west side of Bodega Rock and the submarine ridge at the mouth of the bay. This free shear zone can entrain waters from Bodega Bay and may induce a cyclonic (anticlockwise) circulation in the bay. In the absence of surface wind stress, this recirculation can be expected throughout the water column. However, the surface of the bay is not typically sheltered from the winds that blow along the open coast, because Bodega Head is joined to the mainland by a low-lying sand spit. These equatorward winds blow surface waters south and, through Ekman response, away from the eastern shore of the bay, precluding the development of a resident warm surface layer in the northern bay (in contrast to Monterey Bay [*Graham and Largier*, 1997]). This direct wind forcing is suggested by the strong correlation of equatorward surface flow with wind at the PR site (correlation coefficient = 0.77 at 9 m above bottom).

[23] From the observation of vertically sheared flow at the PR site, it appears that this wind forcing only dominates near-surface waters and that the separation-driven cyclonic recirculation continues at depth in the bay. The argument that this nearshore undercurrent is forced by flow past the mouth of the bay is supported by a strong negative correlation of flow along the open coast (BML site) with near-bottom flow at the PR site (correlation coefficient = −0.80 at 2 m above bottom). In other words, the poleward flow at PR is not in spite of the upwelling, but rather it is due to the upwelling. The poleward flow along the eastern shore of the bay strengthens as the equatorward flow past Bodega Head strengthens. While a large-scale poleward pressure gradient may be present [*Largier et al.*, 1993], this correlation indicates that it is the separation process that controls the strength of this poleward undercurrent nearshore in Bodega Bay. However, this may be enhanced by a local alongshore pressure gradient between BML and PR because of a depression of the sea level during active upwelling along the open coast, although the resolution of the ADCP pressure sensor was inadequate to determine whether this occurred.

[24] In addition to forcing by ambient shelf currents and surface wind stress, upwelling may also impose forcing by the gravity-driven intrusion of cold bottom waters (e.g., Saldanha Bay [*Monteiro and Largier*, 1999]). Cold waters, at depths below 15 m, may only intrude into the southern bay (at the deep entrance, south of the submarine ridge) and then propagate along the east side of the bay. While the bay is small relative to the baroclinic Rossby radius, the effect of

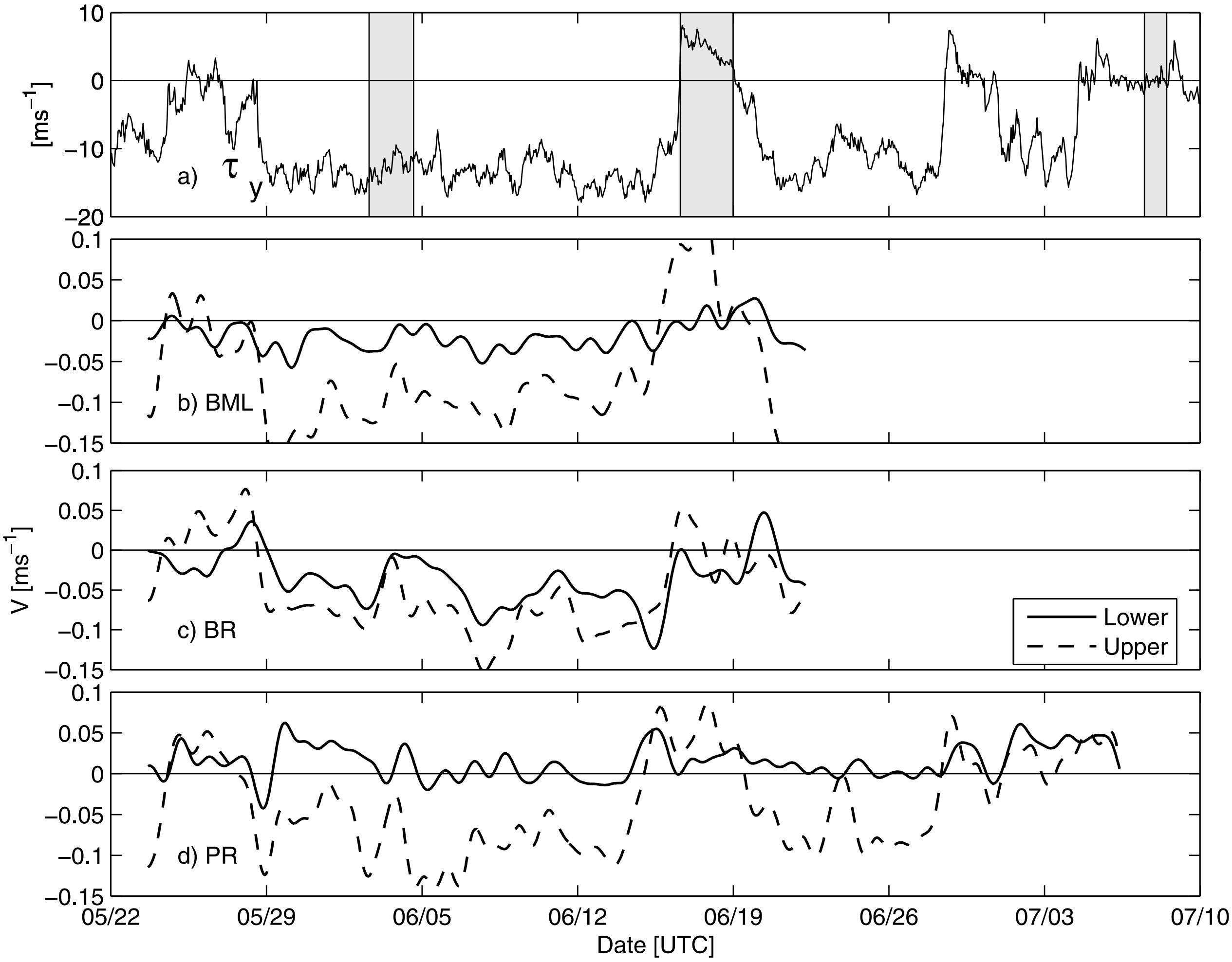

Figure 8. (a) Alongshore component of wind (m s^{-1}) and (b–d) depth-averaged, subtidal, alongshore velocity at BML, BR, and PR. Depth-averaged velocities are calculated for an upper layer (8–10 m above the bottom) and a lower layer (2–6 m above the bottom).

rotation would result in density-driven propagation along the eastern boundary. Southern intrusion and northward propagation of cold bottom water was observed on three occasions during incipient upwelling: 28–29 May, 21–22 June, and 10–14 July. The July event provides the clearest example (Figure 5), with sub-10°C water observed first at T10 (bottom depth ~24 m), followed closely at T02 (open coast, bottom depth ~13 m). In the bay, bottom temperatures only decreased later at T06 and T07 about a day after T10 and T02. The decrease in bottom temperature due to this event was 4–5°C and took more than 3 days to propagate throughout the bay. While this cold water intrusion has a speed consistent with density-driven intrusion, and while the propagation up the east shoreline is consistent with a rotating density current, these data do not allow one to distinguish density-driven intrusion from advection of cold water by the separation-driven cyclonic flow at depth in the bay. However, the burst of near-bottom poleward flow at the PR site on 29 May (Figure 8) suggests that the separation-driven cyclonic circulation is briefly enhanced by the transient density-driven intrusion of cold bottom water. Also of interest during onset of upwelling conditions (e.g., 28 May) was a burst of equatorward flow throughout the water column at PR. At the start of this upwelling event, nearshore winds increased quickly to 7 m s^{-1}, concurrent with winds offshore (Figure 8), so that direct wind forcing on the shallow nearshore waters at PR would have had an immediate effect, whereas the forcing of the cyclonic circulation in the bay would have only evolved a day later following development of a strong equatorward flow over the shelf. A schematic diagram of the circulation within Bodega Bay during upwelling conditions is shown in Figure 10.

3.2. Circulation During Relaxation and Downwelling

[25] Despite the Bodega Bay region having the strongest and most persistent upwelling winds along the west coast of the United States [*Dorman and Winant*, 1995], relaxation periods are common and five events were observed in May–July 2004 in addition to the downwelling event in June (Figure 2). On a large scale, relaxation periods are characterized by strong poleward flow over the inner shelf, that is, past the mouth of Bodega Bay [*Send et al.*, 1987]. While the dynamics have yet to be fully resolved, it is expected that a large-scale seasonal poleward pressure gradient is important in this relaxation [*Largier et al.*,

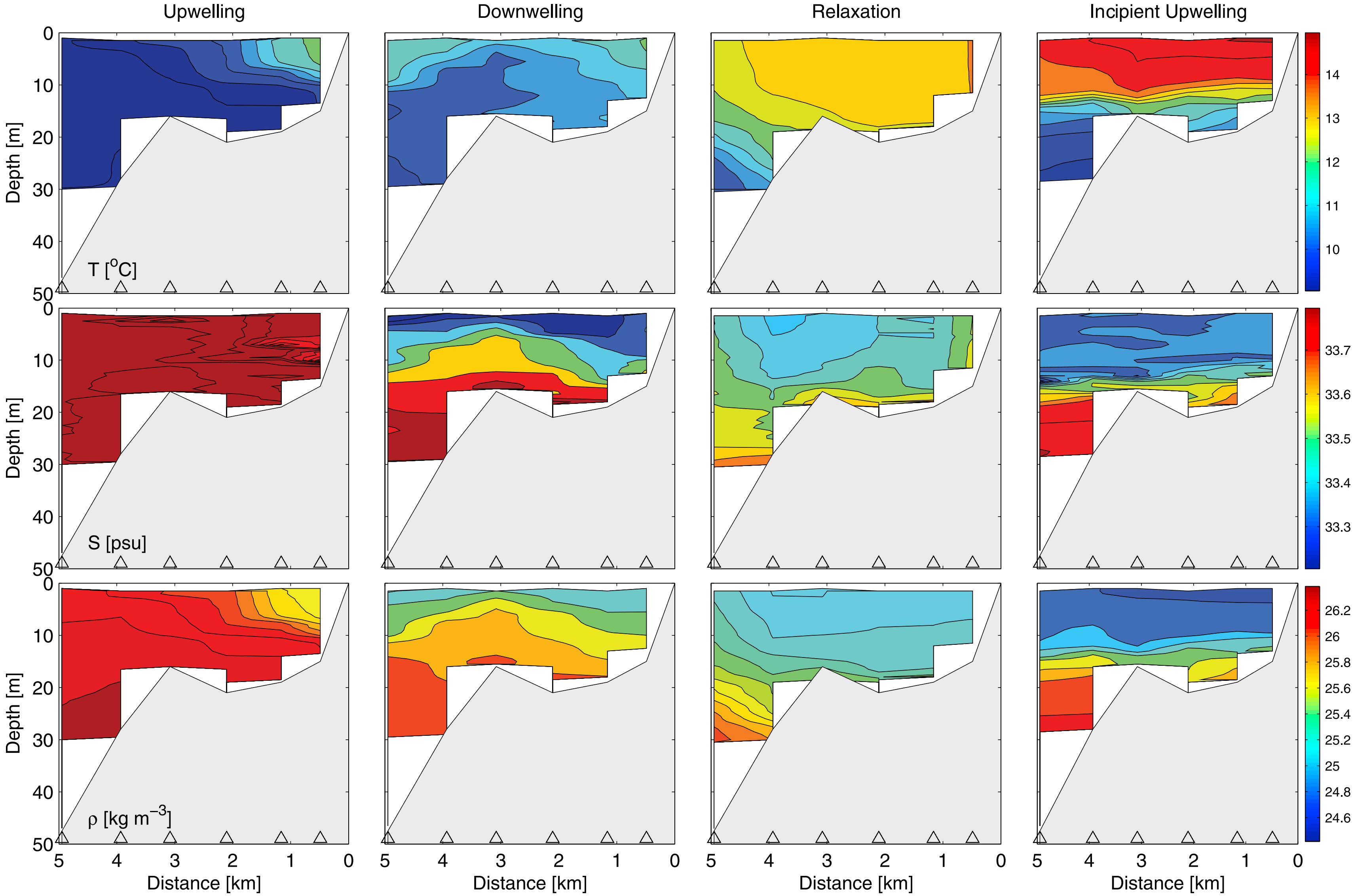

Figure 9. Cross sections of (top) temperature (°C), (middle) salinity (psu), and (bottom) density (kg m^{-3}) along CTD transect 3 (mid bay perpendicular to shore; see Figure 1) during (left to right) upwelling, downwelling, relaxation, and incipient upwelling.

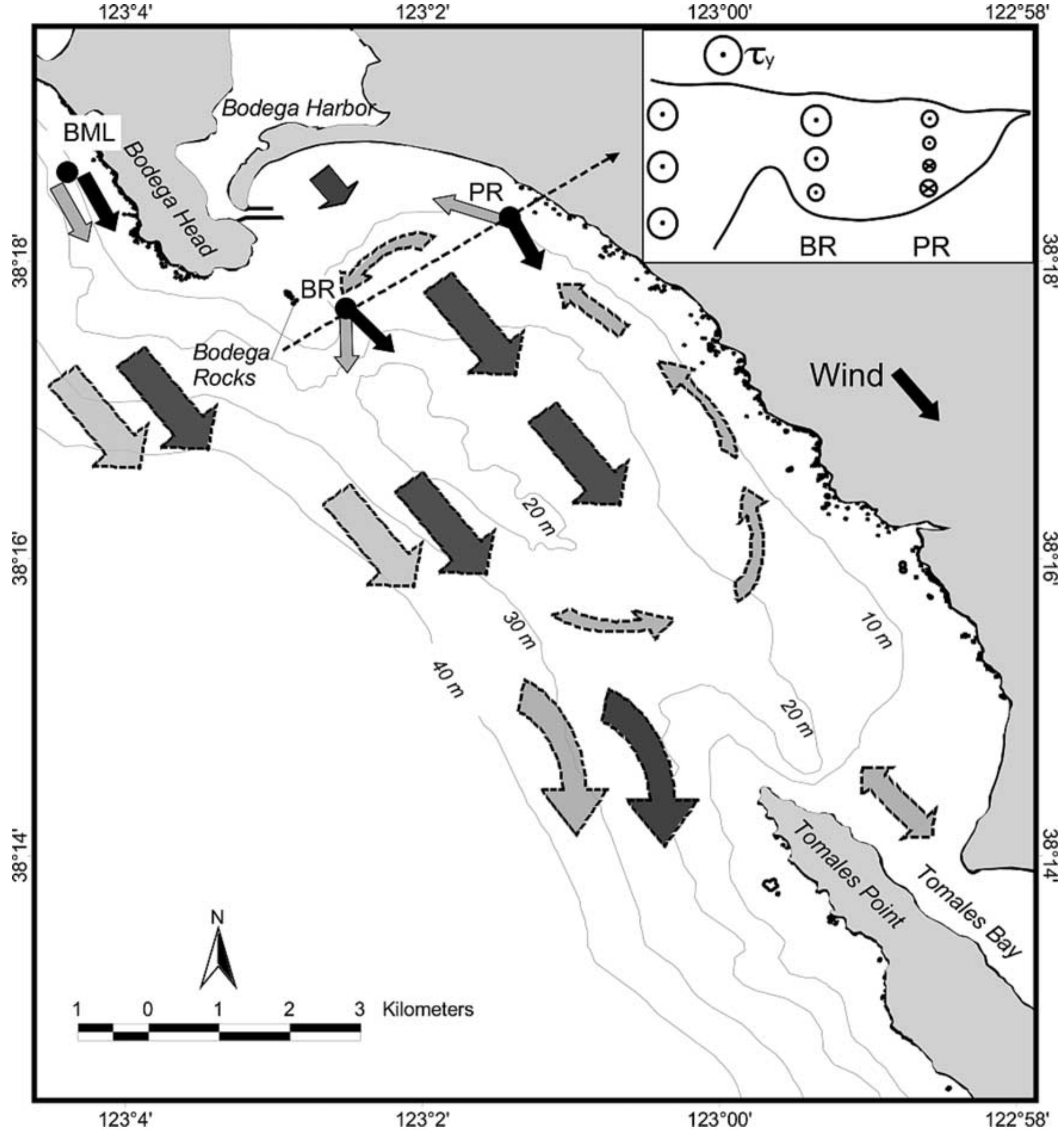

Figure 10. Schematic diagram of flow patterns observed in Bodega Bay under upwelling conditions. Smaller arrows at BML, BR, and PR sites show direction of observed near-surface (dark) and near-bottom (light) currents, whereas larger arrows show postulated near-surface (dark) and near-bottom (light) circulation patterns. Arrows with dashed outlines indicate a flow pattern that is suggested by a combination of observed currents at ADCP sites, drifter tracks on 3–4 June 2004, and gradients in water temperature. Arrows with solid outlines represent flow patterns in which we have confidence because of their proximity to direct ADCP or drifter observations. Arrow length/size is not intended to reflect current speed. The inset shows a cross section of flow in the bay, with vertical shear along the eastern shore and equatorward flow at all depths in the outer bay.

1993; *Gan and Allen*, 2002a, 2002b] and that this may be enhanced by local and more transient barotropic and baroclinic pressure gradients set up during upwelling.

[26] Observations in May–July 2004 describe poleward flow at the PR site in the bay and at the BML site along the open coast (Figure 6) and warming at all depths in the bay. Surface and bottom temperatures increased (Figures 3 and 4) and salinities decreased (~33 psu) (Figure 9), indicating a different water type from offshore or the Gulf of the Farallones. Offshore of the bay, these waters form a surface layer 10–20 m thick and contain high levels of phytoplankton. Warm waters may appear suddenly in the bay (e.g., 25 May and 28 June), first in the south and later in the north, consistent with northward propagation of a thermal front at the leading edge of this new water type. The only relaxation event captured by data from all three moored ADCPs occurred in late May. At the open coast site (BML), equatorward flow began to weaken with the weakening of winds at the offshore buoy (24 May). The subtidal alongshore flow at BML did not reverse during this event, perhaps

because of the brief upwelling wind on 26–27 May. At BR, the near-surface equatorward flow dissipated quickly following the weakening of winds at the shoreline (23 May), and turned onshore and eventually northeastward into the northern bay (Figures 6 and 7). At depth, however, equatorward flow continued for the first few days of relaxation, in concert with BML flows, although this flow also veered more into the bay. At PR, surface flows reversed and diurnal pulses of strong poleward flow (>0.1 m s^{-1}) were observed throughout the water column, both during this event and again during events in early July. This vertical shear is consistent with the appearance of warm waters only at the surface initially (e.g., 25–26 May at T11, Figure 3).

[27] Downwelling events are unusual in this season and only one substantial event was observed in the May–July period. For 2 days in June, poleward winds of about 5 m s^{-1} were observed both offshore and at the coast (Figure 2). This downwelling period was preceded by a burst of equatorward flow at BR, concurrent with a burst of poleward flow at PR (Figure 6), that is, enhanced anticlockwise circulation in the northern bay. This occurred on 15 June, when the upwelling winds had already dissipated over the bay but while strong winds persisted offshore. With the onset of the downwelling winds, flow turned poleward at all ADCP sites (16 June), although this only lasted a day at BR. On 17–18 June, flow was again southeastward out of the northern bay alongside Bodega Rock. By 19 June, a well-developed downwelling structure was observed with isotherms down turned nearshore (Figure 9). Low salinities were also observed, indicating intrusion of a new surface water type.

[28] Thus in contrast to the onset of upwelling on 28 May (when local wind forcing was active, but the alongshore flow forcing had not yet developed), on 15 June it appears that the separation of the alongshore flow at the headland in the absence of local wind forcing may have led to a burst of strong cyclonic circulation in the northern bay. Other periods of enhanced cyclonic circulation (stronger BR equatorward flow matched by stronger poleward flow at PR) were observed around 1 and 7 June.

[29] Once relaxation or downwelling conditions are established, one generally observes an intrusion of new warmer and lower salinity water in the bay; either as a surface layer or throughout the water column. While there may be localized equatorward flow out of the northern subbay in the vicinity of Bodega Rock during active downwelling (presumably due to constrictions on poleward flow out of the bay between Bodega Rock and Bodega Head), there is a general poleward flow of waters through the bay under relaxation and downwelling conditions.

3.3. Transitional Phases

[30] Transitions to and from upwelling conditions were brief and temperature changes occurred rapidly, often in the form of frontal structures that were tidally advected past the moorings. Sudden changes in temperature are most notable with the transition from upwelling to downwelling winds on 16 June (note that winds reversed at BML a day before NDBC 46013, Figure 2). Both surface and bottom temperatures increased suddenly at northern sites (Figure 3), indicating an advection of warm water into the bay [*Send et al.*, 1987; *Wing et al.*, 1995b]. In contrast, transitions to upwelling resulted in sudden decreases in bottom temperatures, indicating the stratified intrusion of newly upwelled waters into the bay. During these transitional conditions, buoyancy forcing appears to be important.

[31] Observations during transition phases allow improved understanding of the interaction of forcing due to wind stress on the surface of the bay and forcing due to separation of the alongshore current at the mouth of the bay. During transition to upwelling, wind forcing starts immediately while alongshore flow across the mouth of the bay develops later, following sea level set-down along the open coast. During this transition phase, with local wind forcing dominant, equatorward flow is observed at all ADCP sites, including all depths at the PR site (e.g., 28 May and 30 June). Rapid hydrographic changes occur throughout the bay during the transition from relaxation to upwelling and are apparent in the CTD surveys on 7 and 11 July (Figure 9). In contrast, during transition to relaxation (or downwelling), winds over the bay weaken immediately while alongshore currents continue across the mouth of the bay for a day (or often longer, owing to the persistence of winds offshore). During this transition phase, with offshore forcing dominant, enhanced lateral shear is observed between PR and BR in the northern subbay. Poleward flow was observed at all depths at PR, equatorward at all depths at BR (e.g., 24 May, 15 June, 28 June, and 4 July) and a burst of anticlockwise flow in the northern subbay on 15 June and again on 1 and 7 July.

4. Variation on the Upwelling Shadow Theme

[32] The concept of upwelling shadows, as described by *Graham and Largier* [1997], has received considerable attention because of the potential importance of these retention zones in upwelling regions. On the basis of the feature observed in northern Monterey Bay, one can identify three key characteristics of an upwelling shadow: reduced local wind forcing, localized reversal of alongshore flow, and warm surface waters. This combination of circulation and stratification is particularly valuable in the retention of both holoplankton and meroplankton and in enhanced primary production by phytoplankton. Elevated temperatures are not only important in terms of stratification, but also because the presence of high-salinity warm waters indicates aged upwelled waters in this region. While similar upwelling shadows are also evident in the northern Gulf of Farallones [*Wing et al.*, 1998], Bahia Mejillones [*Marín et al.*, 2001], and St. Helena Bay [*Penven et al.*, 2000], (among others), these are all larger bays (>10 km). This study in Bodega Bay set out to investigate the possibility of upwelling shadows in smaller bays, such as Bodega Bay (<10 km).

[33] Winds in Bodega Bay are generally weaker than offshore (Figure 2) and relaxation of winds over the bay may occur a day or two prior to offshore. While this suggests that local wind-forced upwelling in the bay is weaker than along the open coast, the small Bodega Head headland does not block nearshore winds, and at times wind forcing along the bay shoreline may be as strong as along the open coast, resulting in active upwelling along the northern and eastern shores of the bay (see surface drifter

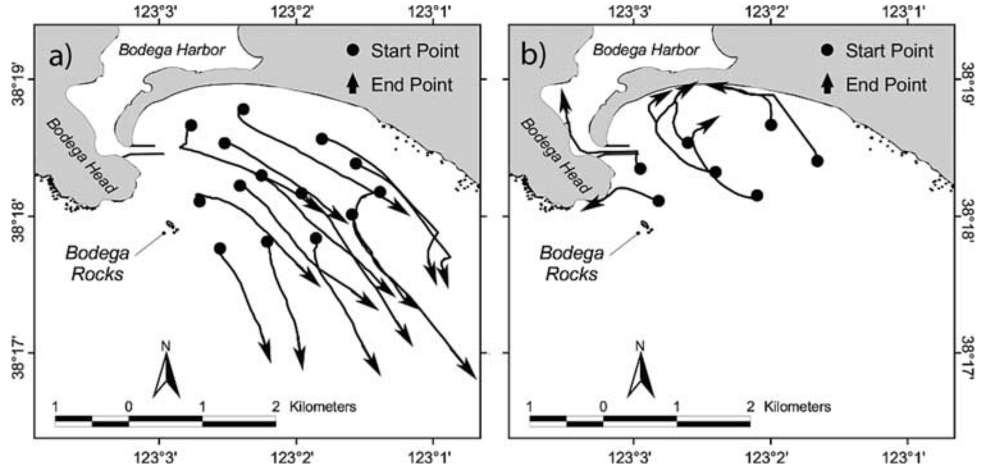

Figure 11. Surface drifter tracks during (a) upwelling conditions (3 and 4 June 2004) and (b) downwelling conditions (19 June 2004).

tracks, Figure 11a, and low temperatures at T01 and T04). Similarly, in-bay upwelling is observed at times in the Farallones upwelling shadow and in the St. Helena Bay upwelling shadow, both of which are also bounded by low-altitude headlands. As a result of this wind forcing of the surface of the bay, recirculation of surface waters is observed only briefly following relaxation of local winds. The absence of near-surface recirculation is presumably due to the near-surface dominance of equatorward wind stress during active upwelling periods. However, recirculation is observed at depth, providing the opportunity for retention of near-bottom or vertically migrating plankton in this small northern subbay. In addition to the vertical shear observed along the eastern shoreline of the bay, near-bottom cyclonic circulation is also reflected in a clear lag in the appearance of upwelled waters from south to east to north. Consistent with the presence of wind forcing in the bay and the absence of inflow and recirculation at the surface, there is seldom a warm surface lens due to retention and warming of upwelled waters in the bay. Thermal stratification is only observed in the northern subbay during incipient upwelling or during upwelling periods when the coastal wind is weak (e.g., warm surface waters were observed at T01 for about a week following the start of upwelling winds on 28 May).

[34] Thus we have observed a variation on the upwelling shadow theme in Bodega Bay that may be common in smaller bays, a variation that does not exhibit near-surface retention, but one that does exhibit recirculation and retention opportunities at depth. This subsurface

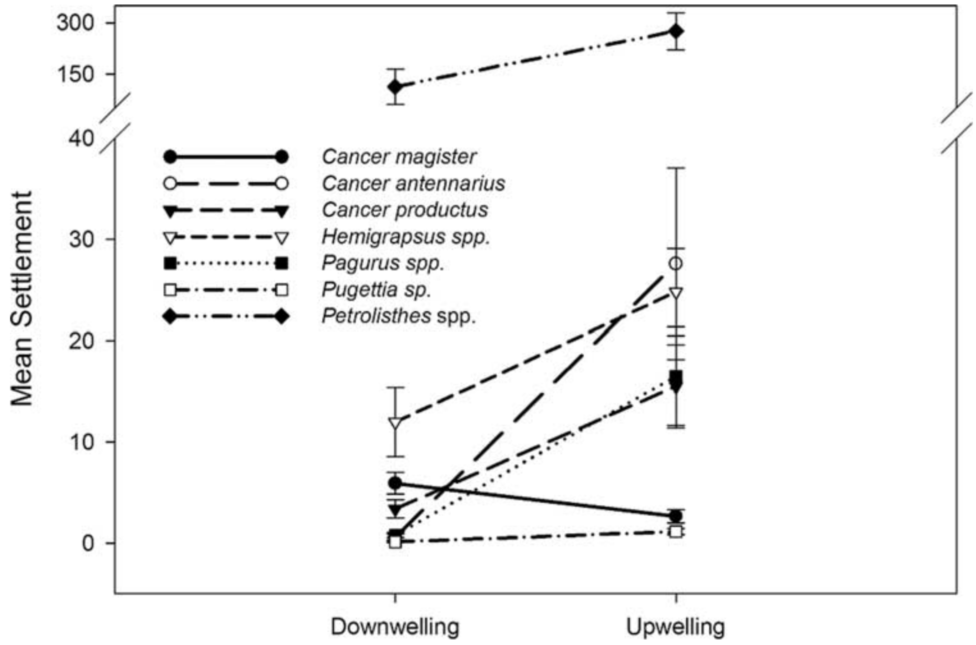

Figure 12. Postlarval settlement of seven crab taxa (±SE) at the PR site during upwelling and downwelling conditions. Note that higher settlement occurred during upwelling for all taxa except *Cancer magister.*

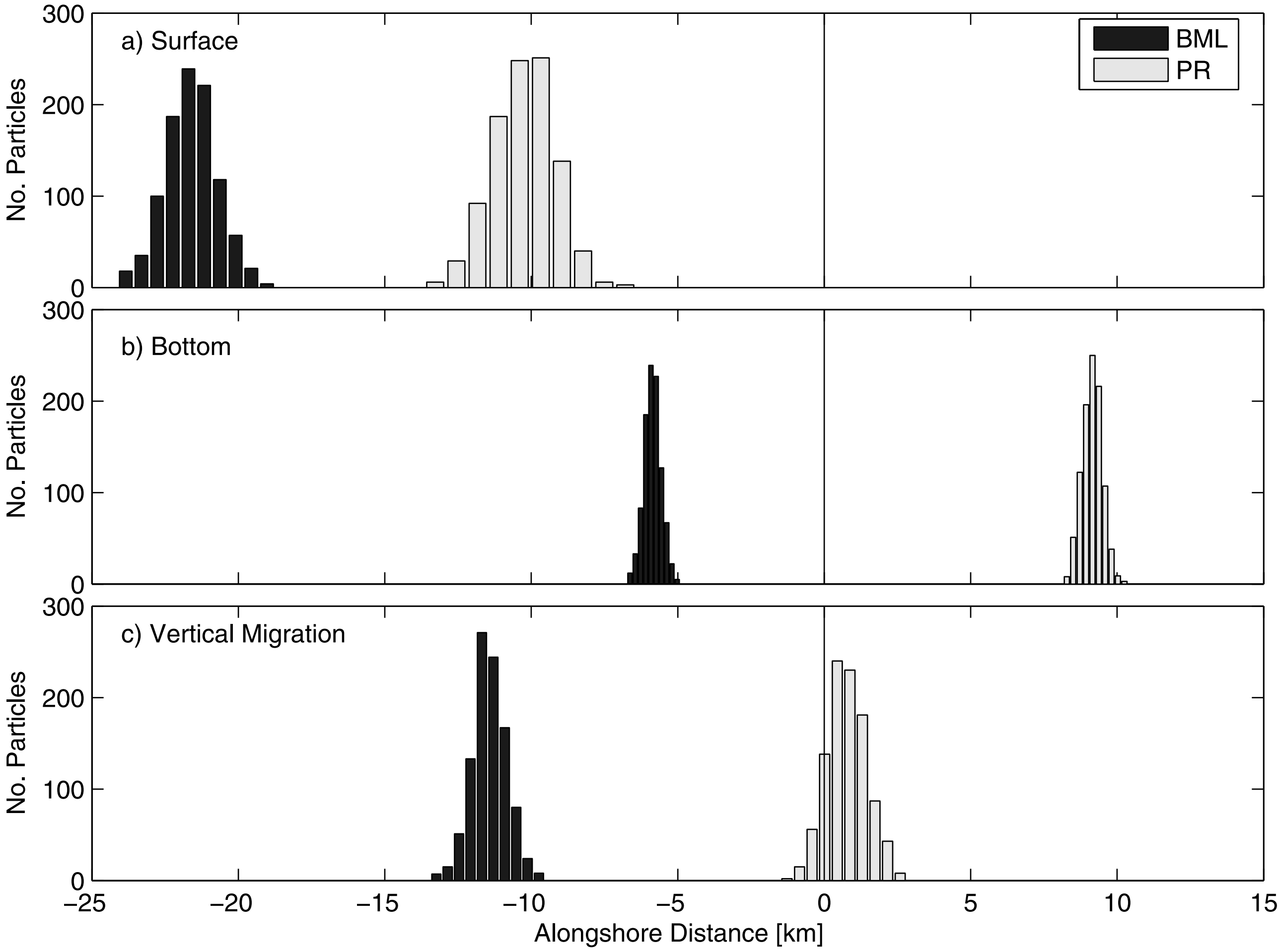

Figure 13. Histogram of the alongshore displacement of particles ("larvae") advected for 3 days by depth-averaged velocities observed at the BML and PR sites during upwelling conditions. Results are shown for the transport of 1000 particles in (a) the upper layer, (b) the lower layer, and (c) a combination of the two layers through diurnal vertical migration with each particle experiencing 9 hours at the surface overnight and 15 hours at depth during daylight hours. The vertical line delineates zero displacement.

upwelling shadow will be of value to a different suite of plankton, specifically those that exhibit vertical migration (e.g., crab postlarvae), rather than those that remain near the surface.

5. Implications for Larval Transport

[35] Postlarvae of nine taxa (*Cancer antennarius, C. magister*, *C. productus*; *Hemigrapsus* spp.; *Pugettia* spp.; *Pagurus* spp.; *Petrolisthes cinctipes*, *P. eriomerus*, *P. manimaculus*) were collected during upwelling (equatorward winds > 5 m s^{-1}) and downwelling (poleward winds >5 m s^{-1}) conditions. Settlement was higher during upwelling (79% of 9,678 crabs) than during downwelling (*df* = 1, *p* value <0.001). Although settlement varied among taxa (*df* = 8, *p* value <0.001) all taxa, with the possible exception of *Cancer magister*, were more abundant during upwelling than downwelling (taxa versus oceanographic condition *df* = 8, *p* value = 0.22) (Figure 12).

[36] We propose that diel postlarval vertical migration and vertical current shear may account for the observed higher rate of settlement during upwelling in the northern region of the bay. Field studies [*Peterson et al.*, 1979] showed the importance of vertical migration in maintaining populations over shelf regions where winds (and thus shelf export) are strong. In the case of Bodega Bay, during periods of upwelling, crab postlarvae may vertically migrate to take advantage of the surface equatorward flow and deep poleward flow, thus allowing them to remain in the bay for longer periods of time. Surface drifter data (Figure 11a) confirm that postlarvae would be exported from the bay during upwelling conditions if they were to remain in surface waters. During periods of downwelling and relaxation, the poleward flow along the eastern shore could act to transport postlarvae poleward, again confirmed by the surface drifter data (Figure 11b). During these conditions postlarvae may be exported out of the bay to the north or may return along the eastern edge of Bodega Rock. Cyclonic recirculation in the bay can be present at depth under most conditions, providing a mechanism for postlarval retention. However, during upwelling, the cyclonic recirculation patterns are strongest because of the separation-driven sheared flow along the eastern edge of the bay, which may account for the

increased settlement observed during strong upwelling favorable winds.

[37] A simple kinematic model was used to investigate the possibility of larval retention in the vicinity of the PR settlement site, where depth-averaged, subtidal velocities in near-surface and near-bottom layers (Figure 8) were used to advect "larvae" for a 3 day period. One thousand particles were released for each of three conditions; upwelling, downwelling, and relaxation and were advected either in the upper layer, the lower layer, or with a combination of diel vertical migration [*Hobbs and Botsford*, 1992]. The vertically migrating particles spent 9 hours in the surface (night) and 15 hours at depth (day) on the basis of the average hours of daylight in Bodega Bay during summer. At each time step the velocities were perturbed with a random white noise component (of the same order of magnitude as the standard deviation of the velocity), which represents the shear dispersion a particle would experience in the ocean. By way of comparison, the same procedure was undertaken at the BML site on the open coast.

[38] During upwelling conditions any "larva" in the surface waters at the BML site would be advected alongshore, away from the local region (traveling 18–24 km equatorward (Figure 13)). By contrast, if larvae were in the surface waters at the PR site, they would only travel 7–14 km equatorward. At depth, particles/larvae at the PR site would be advected 8–10 km poleward compared with 5–6 km equatorward from BML (Figure 13). Clearly, the displacement estimates do not indicate the real destination of particles/larvae, but rather the transport effect in the vicinity of the ADCP similar to a "progressive vector diagram."

[39] The retention benefit of the recirculation at depth can be seen for "larvae" that migrate vertically between the upper and lower layers in response to local light conditions. The majority of particles experienced near-zero alongshore advection at PR (with a maximum advection of 3 km poleward), whereas the same behavior at the BML site on the open coast, (where the current velocity exhibits less vertical shear) does not prevent equatorward transport. Here there was displacement (although reduced) of the order of 12 km, occurring in 3 days (Figure 13). Clearly, the PR site and northern subbay provide a location in which vertically migrating larvae may be retained.

6. Summary

[40] This comprehensive field study, conducted during the summer of 2004, provided a thorough investigation of the flow patterns within Bodega Bay during upwelling, downwelling, and relaxation conditions and allowed for a generalized description of the circulation within Bodega Bay under each wind-forcing regime. The oceanographic data show evidence of a variation on the upwelling shadow theme, where during upwelling, surface waters are flushed rapidly from the bay by strong equatorward winds, yet water is retained at depth in the northern bay through vertical current shear along the eastern shore. Postlarvae settled in higher numbers in the lee of Bodega Head during upwelling conditions, and we propose that postlarvae accumulate in the northern region of the bay by vertically migrating within the sheared flow. Despite the small scale of the Bodega headland, recirculation features are apparent and can facilitate the retention of zooplankton. Hence circulation studies of this scale hold an important place in interdisciplinary marine ecology.

[41] **Acknowledgments.** We thank the numerous people who contributed substantially to the data collection, including Skyli McAfee, Henry Carson, Henry Fastenau, Karl Menard, Joe Newman, Bryan Myers, and Michael Carver. We thank Bodega Marine Laboratory Marine Operations and the Gulf of the Farallones and Cordell Bank National Marine Sanctuaries for their logistical support. We are grateful to Andy Sybrandy and Dario Deihl at SCCWRP for the generous loan of the Pacific Gyre drifters. This work was funded by NSF grant 0098196 and is contribution number 2240 of the Bodega Marine Laboratory.

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