Wind relaxations and poleward flow events in a coastal upwelling system on the central California coast

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[1] When upwelling favorable winds weaken or relax in coastal upwelling systems, prevailing equatorward currents often weaken and then reverse to form propagating poleward currents. Here the statistics of wind relaxations and poleward flow events along the south central California coast are derived using meteorological and oceanographic time series during 2000–2006. Over the 7-year record, 169 wind relaxations were observed (about 1 every 2 weeks) and 127 of these were followed by poleward flow events. Thermistor moorings and current profilers along the 15 m isobath at Alegria, Point Arguello, Point Purisima, and Point Sal recorded the poleward flows. The poleward flows propagate northward at 10–30 km d⁻¹ and appear as sequential temperature increases at the moorings. Wind relaxations occur throughout the year but are most frequent in September and least frequent in April when upwelling winds are strong and persistent. Poleward flows follow wind relaxations frequently during May through November and rarely in December and January. Sea level differences between Santa Monica and Port San Luis, California, decreased as winds relaxed, consistent with forcing by alongshore pressure gradients. Temperature distributions at Point Arguello, Point Purisima, and Point Sal were skewed toward higher values because of the poleward flows. The alongshore distance traveled by the poleward flows increased with duration of the wind relaxations and magnitudes of alongshore temperature and sea level differences prior to the relaxations.


1. Introduction

[2] In eastern boundary currents, equatorward winds drive broad, slow-moving currents equatorward to form the eastern limbs of the anticyclonic subtropical gyres. The California Current System, the eastern boundary current of the North Pacific subtropical gyre, transports a mixture of water masses from higher latitudes equatorward along the California coast [Hickey, 1979; Lynn and Simpson, 1987]. Although the dominant transport of the California Current System is equatorward, poleward flows are important characteristics of the system. Near the coast, poleward currents occur year-round in the California Current System and are most frequent in winter [Hickey, 1979]. North of Point Conception (Figure 1) poleward flow during winter is called the Davidson Current and in the southern California Bight it is called the southern California Eddy, the southern California Counter Current [Hickey, 1979], or the Inshore Counter Current [Lynn and Simpson, 1987].

[3] Poleward flow along the California coast varies over a broad range of time scales due to variations in wind stress, alongshore pressure gradients [Chelton et al., 1988; Harms and Winant, 1998; Hickey, 1979; Hickey and Pola, 1983; Largier et al., 1993], and meridional gradients in wind curl [Oey, 1999]. For example, Chelton et al. [1988] report a 100 km wide by 300 km long poleward flow along the central California coast following a 3-week wind relaxation in 1984. Poleward flows frequently occur over shorter space and time scales. During summer along the central and northern California coast, occasional wind relaxations produce poleward flows and warming over the continental shelf for a few to several days [Largier et al., 1993; Lentz and Chapman, 1989; Send et al., 1987; Winant et al., 1987]. These flows advect warm water retained in lees of capes and headlands poleward [Send et al., 1987]. In addition to transporting heat, these flows also transport larvae of many invertebrate species [Dudas et al., 2008; Mace and Morgan, 2006a, 2006b; Wing et al., 1995a, 1995b].

[4] In the southern California Bight the flow is mostly poleward and exhibits maximum current speeds near the coast during fall [Lynn and Simpson, 1987]. Poleward flows around Point Conception and in the Santa Barbara Channel (SBC) have been characterized over the midshelf (100 m water depths) based on shipboard surveys, drifter releases, and multiyear time series of currents and temperature [Dever et al., 1998; Dever, 2004; Harms and Winant,
A major result from these observations was the identification of synoptic states linking coastal circulation patterns to patterns of wind stress and alongshore pressure gradients. In the SBC, poleward flow along the mainland coast occurs most of the year and is forced by alongshore pressure gradients and southeast winds during winter storms. During the upwelling season (April–September), regional wind relaxations produce transient poleward flows over the shelf often extending around Point Conception and northward along the central California coast. Drifters released in the SBC and Santa Maria Basin (the shelf region offshore of the central California coast north of Point Conception) during winter wind relaxations often reached Monterey Bay and occasionally Point Reyes [Winant et al., 1999; Winant et al., 2003]. Poleward flows around Point Conception are a component of the synoptic relaxation flow state identified by Dever et al. [1998], Dever [2004], Harms and Winant [1998], and Winant et al. [2003]. During summer and fall, midshelf currents respond to repeated cycling between the upwelling and relaxation states with a period of about 2 weeks.

Cudaback et al. [2005] examined the relationship between winds and the temperature and velocity structure on the inner shelf using data from the same moorings as this study. They noted the occurrence of propagating poleward warm currents following wind relaxations, but did not systematically examine the occurrence of these flows or determine characteristics such as frequency or travel distance. This study builds on their results by defining criteria to identify wind relaxations and the poleward flows that follow. The criteria are applied to examine the statistics and characteristics of the propagating poleward flows based on a 7-year record. These flows are important because they transport warm waters from the southern California Bight poleward along the coast where cold upwelled waters persist much of the year. Two-month temperature averages on the shelf north of Point Conception compiled by Winant et al. [2003] show tongues of warm water offshore over the midshelf and separated from the inner shelf by cooler upwelled water nearshore. The events described here temporarily displace the upwelled water offshore and cause rapid temperature increases over the inner shelf.

These observations complement the very extensive set of observations discussed by Dever et al. [1998], Dever [2004], Harms and Winant [1998] Winant et al. [1999], and Winant et al. [2003] by providing details of the inner shelf.
circulation. More recent observations suggest that warm poleward flows occur more frequently over the inner shelf [Cudaback et al., 2005] so statistics based on midshelf observations may not accurately represent their frequency or alongshore extent. Other recent studies have found significant differences in the response of currents to alongshore and cross-shore winds over the inner shelf compared with the midshelf [Fewings et al., 2008; Kirincich and Barth, 2009].

This rest of this paper is organized as follows. The field site, instrumentation, and data processing are described in section 2. This section also describes empirical procedures for identifying wind relaxations and arrivals of warm water at the moorings during poleward flows. In section 3 moored time series are used to illustrate the response of inner shelf currents and temperature to wind relaxations. The response of coastal sea level to wind relaxations and statistics of the poleward flows are also presented in section 3. Section 4 discusses the results, and section 5 presents conclusions.

2. Methods
2.1. Field Site and Instrumentation

An array of moorings along the 15 m isobath was used to study the response of inner shelf circulation to wind relaxations between 1 January 2000 and 31 December 2006. Five moorings were located in the SBC along the south facing coast east of Point Conception at Alegria (ALE), Arroyo Quemado (ARQ), Ellwood (ELL), Arroyo Burro (ARB), and Carpinteria (CAR) (Figure 1). Four moorings were located along the central California coast north of Point Conception at Jalama (JAL), Point Arguello (ARG), Point Purisima (PUR), and Point Sal (SAL). Alongshore distances to the moorings relative to CAR are indicated on the right-hand scale of Figure 2b.

Temperatures at the moorings were measured using thermistors (models UTBI-001 and TBIC32+4+27), manufactured by Onset Computer Corp., Bourne, Massachusetts, mounted on mooring lines at three depths: near bottom (1 m above bottom), middle depth (6 m above bottom), and near surface (12 m above bottom). The manufacturer states the accuracy as 0.2°C and the resolution improved during 2000–2006 as new thermistors were phased in: the first group had a resolution of 0.16°C and the second group 0.09°C. These are adequate for resolving the temperature changes due to the relaxation flows which range from about 1–7°C. Currents through the water column were measured using acoustic Doppler current profilers (ADCP’s, 600 kHz Workhorse Sentinel manufactured by R.D. Instruments, San Diego, California) configured with 1 m bins. The ADCP’s were rigidly mounted to the bottom in an upward-looking orientation a minimum of 10 m from the thermistor mooring lines. To avoid effects of side lobe interference, data from bins nearest the surface were not used. More information about the moorings is given by Melton [2008].

Figure 2. (a) Time series of alongshore wind speed for 2004 at NDBC buoy 46054 (gray line) and from EOF mode 1 reconstruction (black line). (b) Alongshore contours of temperature during 2004 between moorings CAR and SAL. Mooring positions are indicated along the right-hand y axis. Mooring locations are shown in Figure 1. Triangles along the upper x axis identify wind relaxations and propagation extent. Red triangles identify events reaching SAL or beyond, green triangles identify events reaching PUR but not SAL, and blue triangles identify events reaching ARG but not PUR. Yellow triangles identify wind relaxations not followed by arrivals at the moorings. The vertical dotted line indicates time t of a wind relaxation on 11 October 2004 that was followed by a warm poleward flow. The dashed-dotted line indicates a poleward warm flow during a winter storm in February 2004. The slope of the dashed line corresponds to a poleward speed of 20 km d⁻¹.

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velocity data were available during 2000–2004 from the moorings SAMI and SMIN on the 100 m isobath (Figure 1) which were deployed by the Scripps Institution of Oceanography. Currents at these moorings were measured at 5 m and 45 m depth using vector measuring current meters as described by Harms and Winant [1998]. Here the 5 m data were taken as near surface. Additional temperature measurements were occasionally available north of SAL at White Rock (WRK) and San Simeon (SSM) during 2002–2006 (locations of WRK and SSM are indicated on the inset of Figure 1). Time series from these sites were not sufficiently complete for estimating statistics of the poleward relaxation flows, but they do show that the flows occasionally extended beyond the mooring array between CAR and SAL.

2.2. Data Processing

[10] Temperature and current velocity observations were obtained every 2 min and in subsequent processing were low-pass filtered with a cutoff frequency of 1 cycle h\(^{-1}\) and subsampled to 3 samples h\(^{-1}\). At each inner shelf mooring, current vectors were rotated into a principal axis coordinate system based on average subtidal currents from 3 m above bottom (MAB) to the shallowest bin. Principal axis ellipses for the inner shelf moorings were polarized in the alongshore direction consistent with previous observations from these moorings [Cudaback et al., 2005]. Northward 5 m currents at SAMI were taken as alongshore since current direction at SAMI was not strongly polarized in the alongshore direction. Alongshore, poleward currents \(V\) (northward or westward) are positive and onshore currents \(U\) (eastward or northward) are positive. Tidal components were removed from current time series using the program T_TIDE [Pawlowicz et al., 2002].

[11] To quantify wind forcing, hourly wind data were obtained from National Data Buoy Center (NDBC) archives for buoys 46062, 46011, 46023, 46054 (hereafter called the “northern buoys”), and 46053 (Figure 1). Wind vectors were rotated into principal axes coordinates and are presented as \(V\) alongshore (positive poleward) and \(U\) cross shore (positive onshore). Principal axis wind directions (data not shown) are similar to those presented by Cudaback et al. [2005], Dorman and Winant [2000], and Harms and Winant [1998]. Occasional data gaps lasting up to several days occurred in the wind time series between 2000 and 2006 and an extensive gap in all buoys except 46053 occurred from mid-April to early August 2005.

[12] Five high-frequency (HF) radars (Figure 1) measured surface currents (upper 1 m) during 2000–2002, although spatial coverage was inconsistent due to data gaps resulting from power outages and maintenance difficulties. Current time series from the HF radar array are hourly averages interpolated onto a 2 km square grid. Currents vectors are spatial averages of currents within 3 km of each grid point and Emery et al. [2004] describe the processing of the HF radar observations in more detail. Root-mean-square (rms) differences between current velocities measured by HF radar and by current meters are typically of order 0.1 m s\(^{-1}\) [e.g., Emery et al., 2004; Graber et al., 1997; Paduan and Rosenfeld, 1996]. Ohlmann et al. [2007] found RMS differences about half this value when HF radar current velocities were compared with spatially averaged velocities from drifters obtained over areas comparable to the spatial averaging of the radar measurements.

2.3. Alongshore Pressure Differences

[13] Variations in the alongshore pressure differences across the study area were estimated using sea level data obtained from National Oceanographic and Atmospheric Administration (NOAA) sea level gauges at Santa Monica (station 9410840) and Port San Luis (station 9412110). Following Harms and Winant [1994, 1998] effects of sea level difference were evaluated using the subsurface synthetic pressure (SSP):

\[
SSP = P_{\text{atm}} + \rho_0 g \eta
\]

\[
\text{SSP}_{\text{PSL}} = \text{SSP}_{\text{SM}} - \Delta \text{SSP}
\]

where \(P_{\text{atm}}\) is the atmospheric pressure, \(\rho_0\) is average water density, \(g\) is the gravitational acceleration, and \(\eta\) is sea level from the gauges. Time series of \(P_{\text{atm}}\) were obtained from NDBC buoy 46025 (33\(^\circ\)44'20"N, 119\(^\circ\)3'20"W) for Santa Monica and buoy 46011 (Figure 1) for Port San Luis. \(P_{\text{atm}}\) and \(\eta\) were low-pass filtered with a cutoff frequency of 1/36 h\(^{-1}\) to remove high-frequency variability and record means were subtracted to form anomalies \(\delta P_{\text{atm}}\) and \(\rho_0 g \delta \eta\). For example, at Santa Monica (SM) the anomaly \(\delta \text{SSP}\) was defined as

\[
\delta \text{SSP}_{\text{SM}} = \left(\delta P_{\text{atm}, \text{SM}} + \rho_0 g \delta \eta_{\text{SM}}\right)
\]

\[
\delta \text{SSP}_{\text{PSL}}\text{ was defined similarly for Port San Luis. Differences in } \delta \text{SSP}\text{ between Santa Monica and Port San Luis, } \Delta \text{SSP} = \delta \text{SSP}_{\text{SM}} - \delta \text{SSP}_{\text{PSL}}\text{ indicated regional-scale alongshore pressure gradients.}

2.4. Identifying Wind Relaxations

[14] An objective procedure was developed to identify wind relaxations based on wind time series from the northern buoys. Hourly principal axis wind data were low-pass filtered with a cutoff frequency of 1/36 h\(^{-1}\) to remove high-frequency variability such as the diurnal sea breeze. Next an empirical orthogonal function (EOF) analysis was performed as described by Emery and Thomson [1998]. The first EOF mode accounted for 80% of the variance in alongshore winds and captured the upwelling relaxation cycle described by Harms and Winant [1998]. Figure 2a shows good agreement between observed alongshore wind at buoy 46054 and wind reconstructed from the first EOF as \(a_1(t)\varphi_{1,54}\sigma_{54} + V_{54}\) where \(a_1(t)\) is the time varying amplitude function of the first mode, \(\varphi_{1,54}\) is the first mode eigenvector at buoy 46054, \(V_{54}\) is the mean alongshore wind speed, and \(\sigma_{54}\) is the standard deviation. Figure 3 compares \(a_1(t)\) and alongshore winds from the northern buoys during a wind relaxation on 11 October 2004: values of \(a_1 < -1.0\) indicated strong equatorward winds with speeds generally exceeding 10 m s\(^{-1}\), values around zero indicated equatorward winds about 5 m s\(^{-1}\), and values around +1.0 indicated calm conditions.

[15] A wind relaxation was defined to begin at time \(t_b\) when \(a_1\) crossed zero from negative to positive values and was separated by at least 1.5 days from other zero crossings. Additionally, \(a_1\) was required to be positive for at least 70% of a 3-day “upwelling window” (UW, Figure 3) preceding \(t_b\) and negative at least 60% of a 2.5-day “relaxation
For the relaxation of 11 October 2004, a1 was positive during 100% of the upwelling window and negative during 100% of the relaxation window. The ending time of a wind relaxation was defined to occur when a1 crossed zero and remained negative for at least 36 h. The 11 October relaxation ended on 21 October and its duration, defined as \( D_t = t_e - t_b \), was about 10 days (Figure 4a).

### 2.5. Identifying Arrivals of Poleward Flows

A second empirical procedure based on the first derivative of temperature \( dT/dt \) was developed to identify the arrival times \( t_a \) of the propagating, warm relaxation flows at moorings ALE, ARG, PUR, and SAL. Temperature time series from each mooring were averaged over the three measurement depths and low-pass filtered with a cutoff frequency of \( 1/36 \text{ h}^{-1} \). The filtering reduced effects of diurnal heating, tides, and other high-frequency processes. Filtered and unfiltered temperature time series for the wind relaxation of 11 October 2004 are compared in Figure 5b. The \( dT/dt \) was estimated as \( \Delta T/\Delta t \) where \( \Delta T \) was the first difference of the low-pass filtered temperature and \( \Delta t \) = 20 min. \( t_a \) was defined to be the time when \( \Delta T/\Delta t \) reached a maximum exceeding a threshold of 0.031°C h\(^{-1}\). An additional criterion was that an arrival at a mooring must occur after the arrival at the adjacent mooring to the south (equatorward). Figure 5 shows \( t_a \) for arrivals at ALE, ARG, PUR, and SAL. Winds at buoy 46053 and buoy 46054 generally weakened before winds at buoys 46062, 46011, and 46023 and warm events arrived at ALE (and often at ARG) before the identified wind relaxation times \( t_b \). This analysis focused on arrivals at ARG, PUR, and SAL to examine propagation along the central California coast. Figure 5 shows that values of \( t_a \) often were chosen during the temperature rise as the warm water arrived. In some cases a human analyst might have subjectively chosen times a few to several hours earlier based on inspection of the time series. Results of this analysis, however, depend on identifying the occurrences of arrivals and uncertainties in \( t_a \) of hours have little effect on the results presented.

[17] As a check on the procedure for identifying wind relaxations, time series of winds, temperatures, and currents were subjectively examined for all identified wind relaxations and warm water arrivals. Strong poleward winds during winter storms (identified by inspection of wind time series) followed 17 relaxations and any poleward warm flows following these winds were not included as wind relaxation flows. Fifteen relaxations were found that were not identified by the procedure typically because one
element of the procedure was (often just barely) not satisfied. In these cases propagating warm flows were observed at the moorings. Other relaxations were not identified due to missing wind data; 3 occurred during the long gap in wind data of 2005. A total of 169 wind relaxations were identified between 1 January 2000 and 31 December 2006 including the additional 15 ones discussed above.

3. Results

3.1. Wind Relaxations and Poleward Flows

[18] Inner shelf surface temperatures along the mainland coast of the SBC and northward to Point Sal exhibited strong seasonal variations. For example, depth-averaged temperature contours during 2004 versus alongshore distance show coldest temperatures during March through May and warmest temperatures during August through September (Figure 2b). These are consistent with seasonal midshelf (100 m) temperature variability reported by Harms and Winant [1998] and Winant et al. [2003] and inner shelf variability reported by Cupples et al. [2005]. Temperature differences existed most of the year between the regions north and east of Point Conception (Figure 2b). Based on the 7-year record, during June through November temperature differences $\Delta T_a = (T_{ALE} + T_{ELL} + T_{CAR})/3 - (T_{SAL} + T_{PUR} + T_{ARG})/3$ between moorings east of Point Conception (ALE, ELL, and CAR) and moorings to the north (SAL, PUR, and ARG) were 3.2 ± 1.3°C and during December through May were 1.8 ± 0.7°C.

[19] Occasionally for periods of a few to several days, the pattern of warmer temperatures east of Point Conception and cooler temperatures to the north was interrupted by advection of warm water northward around the point and up the central California coast. This occurred when prevailing easterly winds weakened or reversed. In Figure 2 periods of warming caused by this advection appear as bands of higher temperatures extending northward from Point Conception and often reaching Point Sal. One of these events followed the wind relaxation on 11 October 2004 (vertical dotted line, Figure 2). Winter and spring storms also forced warm water north of Point Conception, but they were accompanied by strong poleward winds. An example of a storm-driven poleward warm flow occurred during late February 2004 (vertical dashed-dotted line, Figure 2) when poleward wind speeds at buoy 46054 exceeded 10 m s$^{-1}$.

[20] Examination of the isotherms versus time in Figure 2b reveals that warm waters arrived sequentially at ARG, PUR, and SAL with typical isotherms slopes in the alongshore distance-time plane consistent with poleward propagation speeds in the range 10–30 km d$^{-1}$; the sloping dashed line in Figure 2b corresponds to a propagation speed...
of 20 km d\(^{-1}\). The relaxation of 11 October was followed by temperature increases of about 4°C at ARG on the same day, PUR on 12 October, and SAL on 13 October (Figure 4c). Propagation speed of the nose of the warm water between ARG and SAL was about 28 km d\(^{-1}\). During this wind relaxation equatorward wind speeds dropped from \(24\) m s\(^{-1}\) to near zero over 10 h at the northern buoys (Figures 3 and 4a). Winds relaxed about 1 day earlier at buoy 46053 in the SBC. Cross-shore winds exhibited no clear signature during the relaxation (Figure 4b) and this pattern of a weak or no relaxation signature in cross-shore winds was typical. Warm waters persisted at the moorings until after upwelling winds resumed as found in previous studies in central and northern California [Largier et al., 1993; Mace and Morgan, 2006a; Send et al., 1987; Wing et al., 1995b].

[21] Arrivals of warm water at the moorings produced characteristic patterns in the vertical temperature structure, alongshore flow, and cross-shore flow as exemplified by an arrival at PUR after a wind relaxation on 14 June 2001 (Figure 6a). Warm water arrived nearly simultaneously at the three thermistor depths late on 14 June accompanied by an increase in thermal stratification over the water column compared with the period of upwelling prior to the relaxation (Figure 6b). Arrival time \(t_a\) identified by the procedure of section 2.4 occurred at the beginning of the rapid temperature increase. Warmer, more stratified waters persisted at the mooring for about 2.5 days after \(t_a\) (Figure 6a). Poleward flow increased at all depths beginning about 1 day before the arrival of warm water, but the sharpest increase occurred during the period of most rapid temperature increase (Figure 6c). Poleward flow at PUR exhibited vertical shear as the warm water arrived: it decreased over 8 m from a near-surface speed of 0.35 m s\(^{-1}\) to a near bottom speed of 0.21 m s\(^{-1}\). Middepth speed was intermediate at 0.26 m s\(^{-1}\). Here near-surface flow is the alongshore flow averaged over the upper three ADCP bins centered 12.5 m above bottom (mab), middepth flow is averaged over the middle three bins centered 8.5 mab, and the near-bottom flow is averaged over the lower three bins centered 4.5 mab. Following the peak, alongshore flow at all depths decreased to background values by the end of 15 June.

[22] The cross-shore flow pattern at PUR before the arrival (i.e., before 14 June) was typical of upwelling conditions with offshore near-surface flow, weaker mid-depth flow, and onshore near-bottom flow (Figure 6d).
During the arrival the upwelling pattern reversed to exhibit onshore near-surface flow and offshore near-bottom flow. This flow pattern is typical of downwelling conditions, but Figure 6a shows that it occurred during weakly upwelling favorable winds. Maximum onshore and offshore flow speeds were about 0.1 m s$^{-1}$. Like the alongshore flow, this pattern began about 1 day before the arrival of warm water, but strengthened sharply during the arrival. The cross-shore flow pattern was highly variable for the rest of the relaxation but generally exhibited frequent onshore flow near the surface and offshore flow at depth.

Following the 14 June wind relaxation of fairly constant upwelling winds, diurnal variability at the northern buoys was evident in the alongshore winds throughout the relaxation (Figure 6a). In contrast, strong diurnal variability prevailed at buoy 46053 before and during the relaxation (Figure 6a). Waters at all depths at PUR slowly cooled as upwelling winds strengthened after the end of the wind relaxation on 23 June. Arrival signatures in temperature and velocity at SAL were similar to those at PUR, but often less distinct; one consistent difference was less vertical shear in the alongshore velocity at SAL (data not shown).

Warm water arrived at ARG earlier on 14 June with warming occurring in two steps at all thermistors depths (Figure 7b). Arrival time $t_a$ was chosen between the two steps and nearly coincided with the relaxation time $t_b$. During the arrival cool, nearly uniform temperature upwelled waters were replaced by thermally stratified waters. Temperature at the upper thermistor increased by 7.0°C as warm water arrived at ARG compared with 4.3°C at PUR suggesting that mixing with cooler ambient water occurred during the transit between the moorings. Velocity patterns during the arrival were similar to those at PUR, but flow speeds were greater: maximum alongshore flow was 0.48 m s$^{-1}$ (Figure 7c), maximum onshore near-surface flow speed was 0.18 m s$^{-1}$ and maximum near-bottom offshore flow speed was 0.12 m s$^{-1}$ (Figure 7d). In contrast to PUR, alongshore flow at ARG exhibited little vertical shear, a consistent pattern over many arrivals at this mooring. Two maxima in onshore flow and two minima in offshore flow coincided with the two temperature steps and the arrival signature in cross-shore velocity had faded into the background by around midday on 15 June. A peak in alongshore flow coincided with the first temperature step, but not with the second. This may have resulted from superposition of arrival peaks on diurnal variability in alongshore currents at ARG which commonly occurred at this mooring (Figure 7c).

Satellite sea surface temperature (SST) images showed that warm water associated with the poleward relaxation flows often extended many km offshore and was continuous alongshore. A limitation of SST imagery for observing these flows was that clouds often covered the study area after equatorward winds weakened. SST images before and during the relaxation event of 14 June 2001 clearly showed propagation along the coast and the offshore extent of warm water (Figure 8, corresponding mooring data in Figures 6 and 7). An image on 13 June about 2.5 days before the wind relaxation, showed warm water east of Point Conception and colder water along the coast north of the point with upwelling favorable winds at the northern buoys (Figure 8a). At the time of the image currents were

![Figure 7](image-url)
very weak at SAL, equatorward at PUR and ARG, and poleward at ALE, SMIN, and SAMI. Poleward currents at SMIN, despite the upwelling favorable winds at buoy 46054, likely resulted from regional-scale poleward pressure gradients as discussed by [Harms and Winant, 1998]. For the second image on 14 June which nearly coincided with relaxation time \( t_b \) and ARG arrival time \( t_a \), warm water extended westward from the SBC to ARG and offshore to about 28 km (Figure 8b). Currents at SAL, PUR, ARG, ALE, and SMIN were poleward then even though weakly upwelling favorable winds occurred at buoys 46011 and 46023. Currents from the HF radars along the eastern boundaries of Figures 8a and 8b were also generally poleward. At the time of the next clear SST image on 16 June about 1.7 days after the wind relaxation, warm water extended around Point Conception and up the coast past SAL (Figure 8c). The band of warmer water narrowed with

![Figure 8](image)

**Figure 8.** Satellite sea surface temperature images during 2001 on (a) 13 June at 1001 UT, (b) 14 June at 0951 UT, and (c) 16 June at 0100 UT. Red arrows show wind velocity from NDBC buoys. Black and white arrows show current velocity from HF radar and ADCP’s, respectively. Labeled arrows in Figure 8a show scales for wind and current speeds. Bathymetric contours are thin red lines.

![Figure 9](image)

**Figure 9.** As in Figure 8, but during 2000 on (a) 11 June at 1324 UT and (b) 13 June at 0134 UT.
distance north of Point Conception and was about 17 km wide at PUR at the time of the image. Coincident HF radar current vectors and SST images were available before and during a wind relaxation on 13 June 2000. Strongly upwelling favorable winds were occurring on 11 June when the SST image of Figure 9a was taken about 2.6 days before the wind relaxation. Consistent with these upwelling winds, surface currents offshore and north of Point Arguello were generally equatorward and turned more offshore between Point Arguello and Point Conception. Previous observations have shown a consistent upwelling center between these points [e.g., Atkinson et al., 1986]. Currents in the SBC at SMIN and ALE were poleward at this time. ADCP data were unavailable at ARG and SAL during this event and currents at PUR were very weak at the times of the SST images of Figure 9. An SST image on 13 June, about 5 h after the wind relaxation and just before arrival of warm water at ARG, showed a temperature front extending about 13 km southwest from ARG (Figure 9b). The nearshore region behind the front exhibited onshore flow at the surface consistent with the pattern of onshore near-surface flow during the arrivals at PUR and ARG of Figures 6d and 7d, respectively. Farther offshore and behind the warm front the flow was more alongshore (e.g., around the tip of the white arrow at SMIN in Figure 9b). ADCP observations at PUR during the arrival of this warm flow on 14 June also showed an increase in poleward flow at all depths, onshore near-surface flow, and offshore near-bottom flow (data not shown).

3.2. Wind Relaxations and Changes in Sea Level and Temperature

Wind relaxations occurred year-round and were most frequent in September (n = 23) and least frequent in April (n = 7) as shown in Figure 10. Comparison of wind and sea level time series indicates a link between wind relaxations and changes in alongshore pressure gradients. Anomalies $\rho_o \delta \eta_{SM}$ and $\rho_o \delta \eta_{PSL}$ (Figure 11a) tended to follow each other and were higher than long-term means in summer and lower in winter. Contributions to $\Delta SSP$ from $\delta P_{atm,SM} - \delta P_{atm,PSL}$ were typically smaller than those from $\rho_o \delta \eta_{SM} - \rho_o \delta \eta_{PSL}$ (Figure 11b) especially in summer. Time series of $a_1$ and $\Delta SSP$ were significantly correlated for the 7-year record ($r^2 = 0.27$) with $a_1$ leading $\Delta SSP$ by 17 h. During June–November 2000 when 13 of the 24 wind relaxations for the year occurred, $a_1$ and $\Delta SSP$ were correlated ($r^2 = 0.44$) with $a_1$ leading $\Delta SSP$ by 14 h (Figure 11c).

Local maxima in alongshore temperature difference $\Delta T_a$ usually occurred during or just before wind relaxations (Figure 11d). Rapid decreases following the maxima, such as at the beginning of August 2000, are consistent with transport of warm water by poleward flows from the SBC around the Point Conception and up the central California coast. Following 24 wind relaxations in 2000, 13 warm water arrivals were observed at SAL (Figure 11). Another 8 relaxations were followed by arrivals at PUR, but not SAL, and 1 relaxation was followed by an arrival at ARG, but not PUR.

Although $\Delta T_a$ was nearly always positive (Figure 11d), distributions of $T_{ARG}$, $T_{PUR}$, and $T_{SAL}$ during June–November (when most poleward warm flows were observed) overlapped with the distribution of $T_{ALE}$ (Figure 12). Temperature distributions of $T_{ARG}$, $T_{PUR}$, and $T_{SAL}$ were similar to each other, but different from $T_{AFL}$. Distributions of $T_{ELL}$ and $T_{CAR}$ (data not shown) were similar to the distribution of $T_{AFL}$. The distribution of $T_{AFL}$ had mean and standard deviation $15.3 \pm 1.7^\circ C$, a mode of $16^\circ C$, and was skewed toward lower temperatures (skewness $= -0.28$; Figure 12d). In contrast, $T_{ARG}$, $T_{PUR}$, and $T_{SAL}$ had lower means of $13.1 \pm 1.7^\circ C$,
12.8 ± 1.7°C, and 12.9 ± 1.7°C, respectively, and lower modes, around 12–13°C.

[30] Distributions of $T_{\text{ARG}}$, $T_{\text{PUR}}$, and $T_{\text{SAL}}$ (Figures 12a, 12b, and 12c, respectively) were skewed toward higher temperatures (skewness = 0.33, 0.40, and 0.20, respectively) due to arrivals of warm water following wind relaxations (hereafter called warm events). Gray bars in Figure 12 indicate temperatures over intervals ($t_e + 2 \text{ days}$) before $t_e$ was chosen during the initial temperature increase during an arrival (e.g., Figure 7b). The 2 days added to $t_e$ accounted for the observation that warm water remained at the moorings after $t_e$ (e.g., Figure 7b). The patterns of gray bars of Figure 12 were not highly sensitive to these choices. Warm events accounted for most occurrences of the highest temperatures at ARG, PUR, and SAL. For example, 78–100% of occurrences of $T_{\text{ARG}} \geq 15.5°C$ were during warm events (Figure 12a). At PUR and SAL these ranges were 87–100% and 83–100%, respectively (Figures 12a and 12b). All temperatures greater than 17.5°C at ARG, 16.5°C at PUR, and 17°C at SAL occurred during warm events. At ALE all temperatures greater than 20.5°C occurred during warm events (Figure 12d).

3.3. Propagation of Poleward Flows

[31] Warm events occurred year-round, but were most frequent in September ($n = 19$) and least frequent in December ($n = 3$) as shown in Figure 10 by the heights of gray shaded bars. During 2000–2006, 127 warm events reached ARG (Table 1). Of these 23 did not reach PUR so the northern limits of these events occurred somewhere between ARG and PUR. Similarly, the northern limits for 35 warm events out of the 104 reaching PUR were somewhere between PUR and SAL. Sixty nine events reached SAL or beyond. No warm events followed 27 relaxations and this was most likely in December and January ($n = 7$ each). Warm events were most likely to reach SAL during

- Figure 11. Time series for 2000 of (a) sea level pressure anomalies $\rho_{og} \delta \eta_{\text{SM}}$ at Santa Monica (gray line) and $\rho_{og} \delta \eta_{\text{PSL}}$ at Port San Luis (black line); (b) synthetic subsurface pressure difference $\Delta \text{SSP}$ (black line), difference in sea level pressure anomalies between Santa Monica and Port San Luis $\rho_{og}(\delta \eta_{\text{SM}} - \delta \eta_{\text{PSL}})$ (gray line), and difference in atmospheric pressure anomalies $\Delta P_{\text{atm,SM}} - \Delta P_{\text{atm,PSL}}$ (dotted line); (c) negative of amplitude function of first EOF wind mode $a_1$ (gray line) and $\Delta \text{SSP}/\sigma_{\text{SSP}}$ (black line) where $\sigma_{\text{SSP}}$ is the standard deviation of $\Delta \text{SSP}$; (d) alongshore temperature difference $\Delta T_a$. Vertical lines are wind relaxation times $t_e$. Solid vertical lines indicate wind relaxations followed by warm water arrivals reaching SAL. Dashed lines indicate relaxations followed by arrivals reaching PUR but not SAL. Dash dot lines indicate relaxations arrivals reaching ARG but not PUR.
June–October with a maximum in September (n = 12). No poleward flow events reached SAL in December and only 1 reached SAL in each of January, February, and April. Missing temperature data at one or more moorings prevented identification of warm events following 15 relaxations (Table 1) and they are labeled “no data” in Figure 10.

Distance traveled by the warm events depended on duration of the wind relaxations (\(D_t\)) and alongshore temperature difference (\(D_T\)). Figure 13 shows histograms of numbers of wind relaxations (overall heights of bars) and numbers of warm events at ARG, PUR, and SAL (gray shaded bars) versus \(D_T\). Positive histogram values correspond to \(D_T, \text{max} \geq 2\, ^\circ\text{C}\) and negative values to \(D_T, \text{max} < 2\, ^\circ\text{C}\), where \(D_T, \text{max}\) is the maximum value of \(D_T\) over the 2 days before \(t_b\). Most wind relaxations lasted a few days: of the 151 relaxations sorted in Figure 13 (18 of the 169 total relaxations were not included due to missing data for determining \(D_T\) or \(D_t\)), 100 had \(D_t \leq 5\) days. For relaxations with \(D_t \leq 5\) days, 45 of 83 were followed by warm events reaching SAL when \(D_T, \text{max} \geq 2\, ^\circ\text{C}\) compared with only 1 of 17 relaxations when \(D_T, \text{max} < 2\, ^\circ\text{C}\). For longer wind relaxations, warm events were more likely to reach SAL when \(D_T, \text{max}\) was larger: 19 of 29 relaxations with \(D_t > 5\) days reached SAL when \(D_T, \text{max} \geq 2\, ^\circ\text{C}\) compared with 0 of 22 when \(D_T, \text{max} < 2\, ^\circ\text{C}\). The longest wind relaxation for which arrivals could be identified had \(D_T, \text{max} < 2\, ^\circ\text{C}\) and \(D_t = 28\) days. This relaxation was followed by an arrival at PUR, but not SAL. Nonarrivals at any moorings were more likely for weaker alongshore temperature differences prior to wind relaxations. For \(D_T, \text{max} \geq 2\, ^\circ\text{C}\), 6 of 112 wind relaxations were not followed by arrivals compared with 20 of 39 when \(D_T, \text{max} < 2\, ^\circ\text{C}\). Due to limitations in the detection procedure however, numbers of arrivals for \(D_T, \text{max} < 2\) were likely underestimated.

Patterns of wind speed around arrival times confirm that \(D_t\) was an important factor in determining propagation distance. Figure 14 shows time series of a \(1\)-ensemble-averaged according to propagation distance, denoted as \(\bar{a}_1\), versus time since the beginning of wind relaxations \(t - t_b\). All \(\bar{a}_1\) curves correspond to equatorward winds (compare with Figure 3) and exhibit minima (i.e., stronger equatorward winds) about a day before relaxations followed by increases in \(\bar{a}_1\) over ~2 as days equatorward winds weakened. For 54 relaxations followed by warm events

<table>
<thead>
<tr>
<th>Event</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind relaxations</td>
<td>186</td>
</tr>
<tr>
<td>ARG arrivals</td>
<td>127, northern limit for 23</td>
</tr>
<tr>
<td>PUR arrivals</td>
<td>104, northern limit for 35</td>
</tr>
<tr>
<td>SAL arrivals</td>
<td>69</td>
</tr>
<tr>
<td>No arrivals</td>
<td>27</td>
</tr>
<tr>
<td>Missing data for determining arrivals</td>
<td>15</td>
</tr>
<tr>
<td>Winter storms</td>
<td>17</td>
</tr>
</tbody>
</table>
reaching SAL, $\bar{a}_1$ reached a maximum of 0.76 about 1 day after $t_b$ and remained positive for at least 4 days indicating weak equatorward winds. For a subset of 15 warm events reaching SAL and SSM (located 160 km north of Point Conception, Figure 1), $\bar{a}_1$ indicated even weaker winds for at least 4 days following $t_b$. As an example of long distance propagation, Figure 15 shows sequential temperature increases from ALE to SSM following the 11 October

**Figure 13.** Histogram of wind relaxations and arrivals at moorings sorted by length of wind relaxations $\Delta t_r$. Overall positive and negative heights of bars indicate number of wind relaxations in each bin. Positive histogram values correspond to maximum alongshore temperature difference $\Delta T_{a,\text{max}} \geq 2^\circ\text{C}$ and negative values to $\Delta T_{a,\text{max}} < 2^\circ\text{C}$. $\Delta T_{a,\text{max}}$ is defined in the text. Dark gray bars indicate numbers of warm events arriving at SAL. Medium gray bars indicate number of warm events arriving at PUR but not SAL. Light gray bars indicate number of warm events arriving at ARG but not PUR. Black bars indicate no arrivals following wind relaxations, and white bars indicate insufficient data for determining arrivals.

**Figure 14.** Time series of winds around relaxation times $t_b$ as represented by ensemble-averaged amplitude function of first EOF wind mode $\bar{a}_1$. Ensembles are averaged according to propagation distance alongshore. Dashed black line shows $a_1$ averaged over 15 warm events traveling beyond SAL and reaching WRK. Solid black line is $a_1$ averaged over the 54 warm events reaching SAL, not including the 15 reaching WRK (a total of 69 events reached SAL). Solid dark gray line is the average for the 35 events reaching PUR but not SAL. Solid light gray line is the average for the 23 events reaching ARG but not PUR. Light gray dashed line is the average when no warm events followed wind relaxations. Vertical lines indicate average arrival times at ARG (light gray line), PUR (medium gray line), and SAL (black line).
2004 wind relaxation (also shown in Figures 3, 4, and 5). In contrast, for warm events with propagation limits between ARG and PUR or between PUR and SAL, $\Delta T_a$ reached a maximum less than 1 day after $t_b$ and then rapidly decreased as equatorward winds strengthened. For relaxations not followed by arrivals at ARG, PUR, or SAL, $\Delta T_a$ remained higher following $t_b$ and exhibited a weaker maximum before $t_b$. These were a subset of mainly winter relaxations with $\Delta T_a < 2^\circ C$ which did not result in warm events reaching SAL regardless of $\Delta t_r$. Following $t_b$, warm events arrived at ARG about 0.7 days later, at PUR about 1.8 days later, and at SAL about 2.6 days later (vertical lines, Figure 14).

Most warm events occurred when $\Delta SSP_{max}$ was positive, consistent with advection due to poleward pressure gradients setup by regional sea level differences. Figure 16 is a histogram of $\Delta SSP_{max}$, the maximum values of $\Delta SSP$ within the 3-day interval before the wind relaxations. This interval was chosen because $\Delta SSP$ typically exhibited local maxima within 1–3 days of wind relaxations (Figures 11b and 11c). Of the 157 wind relaxations for which data were available for estimating $\Delta SSP_{max}$, 27 warm events occurred when $\Delta SSP_{max}$ was near zero (within ±0.05 kPa) and 102 occurred when $\Delta SSP_{max} > 0.05$ kPa. A higher fraction of warm events reached SAL when $\Delta SSP_{max}$ was large: 25 of 35 warm events reached SAL when $0.25 \leq \Delta SSP_{max} < 0.55$ kPa, compared with 24 of 58 when $0.05 \leq \Delta SSP_{max} < 0.25$ kPa. For larger $\Delta SSP_{max}$, one warm event reached PUR, one relaxation was not followed by a warm event, and data were not available after one relaxation event. Sixteen warm events occurred when $\Delta SSP_{max} < -0.05$ kPa with the number decreasing rapidly as $\Delta SSP_{max}$ became more negative. With one exception, all wind relaxations not followed by warm events occurred for weak ($|\Delta SSP_{max}| < 0.25$ kPa) or negative $\Delta SSP_{max}$.

Poleward flow during wind relaxations was more common over the inner shelf than midshelf (100 m water depth) during 2000–2004 when current data were available simultaneously at PUR and SAMI. Alongshore velocity data were compared from PUR and SAMI to examine the relative occurrence of poleward flows over the midshelf compared to the inner shelf. For all warm events reaching PUR, alongshore near surface currents at PUR and SAMI were averaged during intervals $\Delta t_r$ encompassing wind relaxation events. Of the 65 warm events with simultaneous current data at PUR and SAMI, 62 events at PUR and 33 at SAMI corresponded to poleward flow (Figure 17). Poleward flow at SAMI was more likely for larger temperature increases during arrivals at PUR (\Delta T_{PUR}): 11 of the 33 warm events with poleward flow at SAMI occurred when $\Delta T_{PUR} \geq 2^\circ C$ compared with 4 of 32 events with equatorward flow at SAMI. Here $\Delta T_{PUR}$ was defined as the temperature at PUR averaged 24 h after $t_a$ minus the temperature 24 h before $t_a$.

### 4. Discussion

The generation of poleward flows following wind relaxations of upwelling favorable winds is a general
characteristic of the eastern boundary current upwelling systems. Similar flows have been observed off the Iberian Peninsula in the Portuguese-Canary Current System of the North Atlantic [García-Lafuente et al., 2006; Relvas and Barton, 2002, 2005]. Relvas and Barton [2002] used satellite SST imagery to show that following relaxation of upwelling winds, a warm coastal countercurrent can flow westward from the Gulf of Cádiz and occasionally (~20% of the time) round Cape São Vicente to propagate northward up to 100 km along the west coast of Portugal. This anticyclonic turning of the flow at Cape São Vicente resembles the flow pattern around Point Conception. The propagation speed of a warm relaxation flow reported by Relvas and Barton [2002] (which they refer to as a countercurrent) was about 0.16 m s\(^{-1}\) which is within the range of speeds for the flows along the California coast. Tide gauge observations around the Cape São Vicente indicate that the countercurrent was driven by alongshore pressure gradients much like the flows reported here. The width of the countercurrent was 15–25 km, similar to the widths of the flows on the California coast. Hydrographic and ADCP shipboard surveys showed that the countercurrent was confined to the continental shelf [García-Lafuente et al., 2006; Relvas and Barton, 2005] and that it originated from warm water flowing westward along the coast from the Gulf of Cádiz.

Warm poleward flows often follow wind relaxations or reversals in the Benguela Current upwelling system. Fawcett et al. [2008] obtained current and temperature time series over the continental shelf of the southern Benguela Current near Cape Columbine. During the upwelling season they found that when equatorward winds relaxed or reversed, currents reversed from equatorward to poleward and temperatures increases by up to 5°C. Like Send et al. [1987] they concluded that the large temperature changes resulted from advection rather than solar insolation. During their study periods in winter and early and late in the upwelling season, wind relaxations typically lasted up to 5 days, comparable to lengths of relaxations reported here most of which were 5 days or less (Figure 13).

These poleward relaxation flows, and those described by Relvas and Barton [2002, 2005], share characteristics with buoyant coastal currents that originate in the Chesapeake Bay and propagate equatorward along the North Carolina coast [Johnson et al., 2001; Lentz et al., 2003; Lentz and Largier, 2006; Rennie et al., 1999]. In these systems buoyant currents propagate alongshore into ambient waters with higher density with the coastline to the right of the propagation direction. In the currents from the Chesapeake, buoyancy differences arise from lower salinity and in the relaxation flows they arise from higher temperature. Velocity signatures during arrivals of relaxation flows reported here exhibited increased poleward flow at all depths and onshore flow near the surface, much like during arrivals of low-salinity water from the Chesapeake [Lentz et al., 2003]. In the Chesapeake and California systems alongshore flow increases before the arrival of the buoyant water, but the timing is different. For the Chesapeake plumes, alongshore flow precedes arrivals of low-salinity water by a few hours suggesting that the nose of the propagating buoyant current pushes water alongshore and aside much like a moving bluff body [Lentz et al., 2003]. In contrast, the poleward flows observed in this study precede the arrivals of warm water by a day or more. For example, following a wind relaxation on 14 June 2001, poleward flow at PUR and SAL began a day or more before the arrivals of warm water as shown in Figures 6c and 7c. The HF radar current pattern of Figure 7b, also shows poleward
flow ahead of the warm water. We speculate that this rapid response of the inner shelf velocity field results from alongshore barotropic pressure gradients set up by sea level differences north and east of Point Conception. Similar forcing of inner shelf currents by poleward pressure gradients along the Oregon coast has been simulated in numerical modeling experiments by Gan and Allen [2002]. García-Lafuente et al. [2006] and Relvas and Barton [2002] also invoke alongshore pressure gradients for driving the countercurrents they observed in the Gulf of Cádiz. The poleward flow typically increases again a few to several hours before the arrival of the warm water with the peak alongshore flow approximately coinciding with maxima in dT/dt at the moorings.

Figure 17. Alongshore current velocity at PUR and SAMI for all warm events when data were available at both moorings. Velocities are averaged over wind relaxation intervals Δt, as explained in text. Positive velocities are poleward. Open circles correspond to temperature changes at PUR during arrivals ΔT_PUR ≥ 2°C and filled circles to ΔT_PUR < 2°C. ΔT_PUR is defined in the text.

5. Conclusions

Studies along the northern California coast have shown that warm coastal currents following wind relaxations are important in the poleward transport and settlement of larvae in wind-driven coastal upwelling systems. Mace and Morgan [2006a] found that settlement of Cancer magister larve in Bodega Bay, California increased during relaxation events. In contrast, they found that other species such as C. attennarii and C. productus settled during upwelling conditions. North of Point Reyes, California, Wing et al. [1995a] found that high settlement of crab larvae only occurred following relaxation events. South of Point Reyes settlement occurred during upwelling conditions, but was stronger during relaxation events. More recently Dudas et al. [2008] report that high barnacle recruitment at sites along the Oregon coast was associated with more frequent poleward flow, increased onshore flow, and higher temperatures, all of which suggest that relaxation flows are the underlying larval delivery mechanism. Few studies have examined links between larval fish settlement and oceanographic conditions, but a recent example suggests relaxation flows can lead to increased settlement. Wilson et al. [2008] found that increased settlement of the kelp-copper-gopher-black (KCGB) rockfish complex was correlated with warmer water temperatures along the central California coast consistent with larval delivery by relaxation flows.

Patterns of settlement rates of some invertebrate such as the mussel Septifer bifurcans decrease rapidly north of Point Conception (C. Blanchette, personal communication, 2008). This is consistent with occasional delivery by warm poleward flows, although verifying this speculation will require process studies linking settlement to coastal circulation. Point Conception is a major biogeographic boundary along the west coast of North America for many marine species and the role of coastal circulation patterns in its maintenance remains an open question [Briggs, 1974; Burton, 1998; Doyle, 1985; Gaylord and Gaines, 2005; Newman, 1979; Valentine, 1966]. The new and relevant result from these observations is that poleward currents through this biogeographic boundary are common over the inner shelf where many subtidal and intertidal species settle.
days and the modal duration was 2 days. The widths of the flows were variable and extended up to ~20 km offshore based on satellite SST images. Poleward alongshore currents during wind relaxations occurred about twice as often on the inner shelf compared with the midshelf (100 m water depth). Propagation distances of the warm poleward flows increased with (1) longer durations of the wind relaxations; (2) larger alongshore temperature differences between the coasts north and east of Point Conception; and (3) larger sea level differences between the southern California Bight and central California. Over half of the poleward flows reached Point Sal and a few propagated at least to San Simeon, California, 160 km north of Point Conception. This is consistent with other studies such as that of Winant et al. [2003] who showed tracks of drifters released in the Santa Barbara Channel and the Santa Maria Basin (the area offshore of mooring ARG, PUR, and SAL in Figure 1) occasionally reached Monterey Bay 300 km north of Point Conception.

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