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A poleward jet and an equatorward undercurrent observed off Oregon and northern California, during the 1997–98 El Niño

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Abstract

The timing and intensity of the effects of the 1997–98 El Niño on sea-surface temperature (SST) and coastal sea level along the US west coast are examined using in situ time-series measurements, and the effects on upper ocean currents on the continental shelf and slope off Oregon and northern California are examined using repeated shipborne ADCP transects, a mid-shelf mooring off Newport Oregon and an HF surface current radar. An initial transient positive anomaly was observed in both adjusted sea level and SST during May–June 1997, followed by anomalously high coastal sea levels, generally strongest during September 1997 through February 1998 and abruptly returned to normal in late February 1998, and by positive temperatures anomalies over the mid-shelf that persisted longer, into April 1998. Low-frequency coastal sea-level anomalies propagated poleward at 2.1 m/s. Poleward flow over the shelf and slope was enhanced at most depths during the El Niño, compared with following years. Northward currents in the upper 12 m over the continental shelf off Newport, Oregon averaged 13.7 cm/s stronger during August 1997 through February 1998 than during the same period the following year. Enhanced poleward flow was present at all latitudes sampled during November 1997 and February 1998, particularly over the continental slope. These transects also provided clear views of a fall/winter equatorward undercurrent, which was both strongest and had the most alongshore similarity of form, during the ENSO. Finally, subsurface-intensified anticyclonic eddies originating in the poleward undercurrent appear to be a recurrent feature of the circulation off Newport late in the upwelling season. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: El Niño phenomena; Coastal jets; Coastal currents; Continental slope; Undercurrents; Sea level

1. Introduction

Midlatitude observations of earlier El Niños have shown profound effects on coastal sea level, water temperature, and salinity off the US west coast (Chelton & Davis, 1982; Wooster & Fluharty, 1985; Huyer, Smith, & Fleischbein, 2002). These changes may be driven directly by changes in atmospheric forcing

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(Schwing, 1998; Schwing, Murphee, & de Witt, 2002) as well as through alongshore-propagating waves (Enfield & Allen, 1980).

Direct observations of the current fields over the northern hemisphere shelf and slope during El Niño appear to be less commonly available. The seasonal cycle of currents over the Oregon continental shelf was first summarized by Huyer, Pillsbury, and Smith (1975), based on a one-year time series at a midshelf mooring, plus numerous short records from different years. They found a surface-intensified, vertically-sheared equatorward coastal jet in alongshore currents during spring and summer, and a largely unsheared poleward current during the winter, which was strongest near the coast. Analysis of the seasonal cycle in direct current measurements at five latitudes between 48.3°N and 34.7°N found the winter phase to be poleward at 5–15 cm/s at all mooring locations along the coast and across the shelf (Strub, Allen, Huyer, Smith, & Beardsley, 1987). Lentz and Chapman (1989); Largier, Magnell and Winant (1993), and Collins, Garfield, Paquette, & Carter, (1996a) similarly describe the seasonal cycles of directly-measured currents off northern and central California.

Increased poleward advection of 7 to 21 cm/s, associated with the onset of El Niño, has been observed at a mid-shelf current meter on the Peru shelf during the 1976 and 1982–83 El Niños (Smith, 1983), and on the Oregon shelf during the 1982–83 event (Huyer & Smith, 1985).

Over the continental slope, the space and time structure of the low-frequency currents is much less well known, as is the response to El Niño. The passage of warm-core eddies is documented off Oregon (Huyer, Smith, & Hickey, 1984) and off Monterey (Ramp, Rosenfeld, Tisch, & Hicks, 1997) using direct current measurements. Collins, Paquette, & Ramp, (1996b) described the seasonal variability in currents at 350 m depth over the upper slope off Point Sur, California. Kosro et al. (personal communication) give a seasonal picture of the slope currents off northern California, including the seasonal cycle of the poleward undercurrent. Recent studies have used subsurface floats to trace the undercurrent and its spin-off eddies (Garfield, Collins, Paquette, & Carter, 1999).

The effects of the 1997–98 El Niño on the US northwest coast are examined below using in situ measurements. Sea-surface temperature (SST) and sea level time-series are used to determine the timing, alongshore extent and intensity of the response, and to observe the northward propagation of the associated sea-level anomalies. Direct current-measurement time-series over the Oregon shelf are used to compare the alongshore flow during the 1997–98 ENSO period with the following year. Then, seasonally-repeated shipbased ADCP transects are used to provide snapshots of the alongshore flow over the continental shelf and slope at several latitudes before, during and after the El Niño.

2. Data and methods

In July 1997, we began a multidisciplinary Long-Term Observation Program (LTOP) to conduct seasonally-repeated sampling of transects crossing the California Current off Oregon and Northern California, as part of the US GLOBEC Northeast Pacific program (Fig. 1; Table 1). Cruises were scheduled to sample the circulation near the start, middle, and end of the upwelling season, as well as once in the fall and once in the winter. The Newport Hydrographic (NH) section was sampled on every cruise. The Five-Mile (FM) section off Coos Bay, Oregon, and the Crescent City (CR) section were sampled on most non-winter cruises, and the Eureka (EU) section was sampled on five cruises during 1998 and 1999. Measured parameters include vertical profiles of conductivity and temperature from CTD (Fleischbein, Hill, Huyer, Smith, & Wheeler, 1999; Huyer et al., 2002), nutrients and fluorescence (Wheeler & Corwith, 2002), as well as measurements of zooplankton species and abundance (Peterson, Keister, & Feinberg, 2002). Currents across each transect were inferred from density measurements by the geostrophic method (Huyer et al., 2002).

Upper-ocean currents also were measured directly along each transect using a shipborne acoustic Doppler

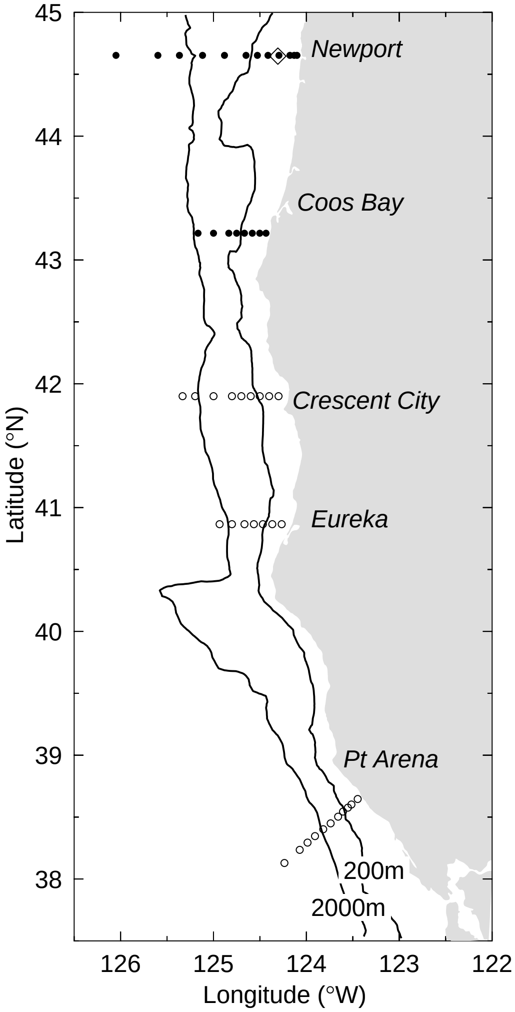

Fig. 1. Locations of CTD stations along selected transects, which were repeatedly sampled in the GLOBEC program between 1997 and 2000. Most transects are east–west, e.g. at 44.6°N (Newport Hydrographic, or NH, Line), 43.2°N (Five Mile, or FM), 41.9°N (Crescent City, or CR), 40.9°N (Eureka, or EU). A transect corresponding to the CODE Central Hydrographic Line was also occupied south of Point Arena, California (38.6°N, 123.6°N to 38.3°N, 124.2°N). The NH and FM lines, shown using solid symbols, were occupied the most frequently (see Table 1). The location of the NH-10 mooring (44.6°N, 124.3°W) is shown as an open diamond on the Newport Line.

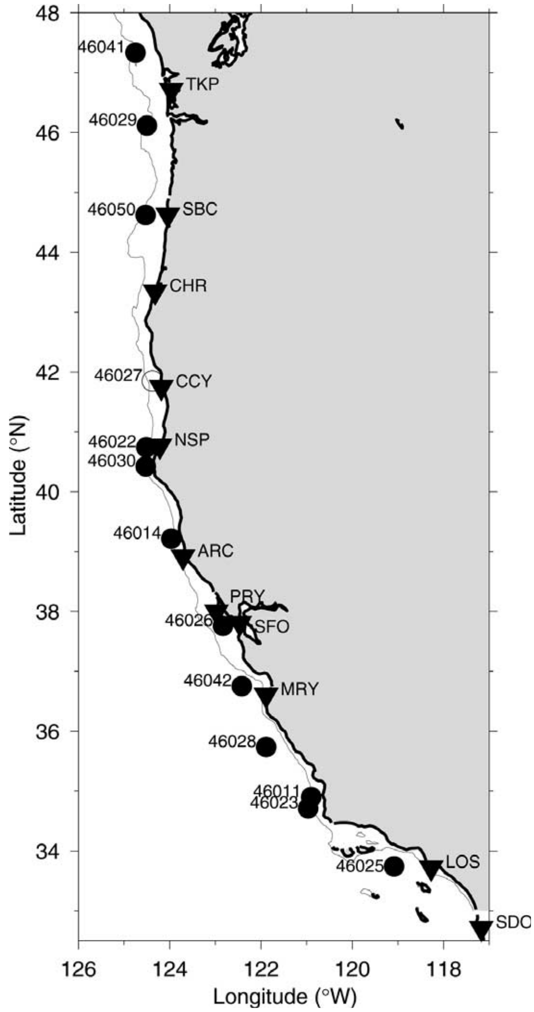

Fig 2. Locations of offshore environmental buoys (circles) and tide gauges (triangles) used in this analysis, along with the 200 m isobath. Buoys and tide gauges are maintained by the National Data Buoy Center (NDBC) and the National Ocean Service (NOS), respectively. NDBC buoy numbers are indicated. Tide gauge data were used from Toke Point (TKP, 46.7°N), South Beach (SBC, 44.6°N), Charleston (CHR, 43.3°N), Crescent City (CCY, 41.7°N), North Spit (NSP, 40.8°N), Arena Cove (ARC, 38.9°N), Point Reyes (PRY, 38.0°N), San Francisco (SFO, 37.8°N), Monterey (MRY, 36.6°N), Los Angeles (LOS, 33.7°N), and San Diego (SDO, 32.7°N).

Table 1
Wecoma LTOP and related cruise names, dates, and sections sampled using shipborne ADCP (zonal sections are NH (44°39’N), FM (43°13’N), CR (41°54’N), and EU (40°52’N); section COC ran from COC-2 (38°38.3’N, 123°26.9’W) to COC-11 (38°17.6’N, 123°59.3’W) or COC-13 (38°07.8’N, 124°14.1’W))

Cruise	Dates	NH	FM	CR	EU	COC
W9707B	28–30 July 1997	x				
W9709B	19–20 Sept 1997	x				
W9711C	15–22 Nov 1997	x	x	x		x
W9801B	30 Jan–2 Feb 1998	x	x			
W9804B	4–10 Apr 1998	x	x	x	x	x
W9808A	6–11 Aug 1998	x	x	x	x	x
W9809A	24–26 Sept 1998	x				
W9811A	16–20 Nov 1998	x	x	x	x	
W9902A	17–18 Feb 1999	x				
W9904B	19–23 April 1999	x	x	x		
W9907A	3–9 July 1999	x	x	x	x	
W9909C	22–27 Sept 1999	x	x	x	x	
W9911A	3–5 Nov 1999	x				
W0002A	1–3 Feb 2000	x				
W0003A	28–29 Mar 2000	x				
W0004B	11–17 Apr 2000	x	x	x		

current profiler (ADCP, narrowband 153 kHz, 8 m bins, manufactured by RD Instruments). Shipborne ADCP data were collected in 2.5 min ensembles, and processed using the University of Hawaii CODAS database system and tools (Firing, Ranada,& Caldwell, 1995). Profiles were screened manually for bottom-interference, corrected for dynamic gyrocompass errors with data from an Ashtech 3DF GPS-based system, calibrated for misalignment of the transducer and gyrocompass (Kosro, 1985; Pollard & Read, 1989;Pollard, 1989 Joyce, 1989), and processed to absolute currents by referencing to differential GPS data. Based on the mid-shelf moored measurements discussed below, diurnal, semidiurnal and inertial currents are expected to contribute about 8 cm/s in combined high-frequency fluctuations to the instantaneously measured northward current component, representing approximately 11% of the variance in that component.

Moored current-profile time-series data were collected in 81 m of water from upward-looking acoustic Doppler profilers (ADPs) manufactured by Sontek (500 kHz, 2 m bins) on the continental shelf near 44°39’N, 124°18’W, at a location several kilometers south of LTOP hydrographic station NH10 (Fig. 1). The first three deployments of the NH-10 mooring were from 9 August 1997 to 14 October 1997, 21 October 1997 to 4 April 1998, and 1 May 1998 to 29 July 1998. Sampling was for 50 s every 150 s, 120 s every 300 s, and 60 s every 180 s, for the three deployments, respectively. Data were corrected from magnetic to geographic coordinates and assigned depths below the surface, based on surface reflection and the 2 m bin size. Hourly averages centered on the hour were produced, and these were then low-pass filtered using a cosine-Lanczos filter with 40 h half-power cutoff. Data from the second deployment were cut short when a battery cell leaked inside the pressure case, destroying the internal electronics; the last valid data on this deployment were collected on 30 December 1997, leaving a time-series gap of 4 months.

An HF surface-current mapping radar system (SeaSonde, manufactured by CODAR Ocean Sensors) (Barrick, Evans, & Weber, 1977; Lipa & Barrick, 1983) provided an additional source of directly measured currents. We have operated a pair of 12 MHz systems encompassing the NH Line continuously since November 1997. Correlations between identically low-pass-filtered currents from the radar (surface) and 10 m bin of the ADP were 0.84 and 0.94 for eastward and northward components, respectively, with differences whose standard deviations were approximately 10 cm/s. This indicates that not only are the differences large but also the common signal is large.

Environmental buoys maintained along the US west coast by the National Data Buoy Center (NDBC) of NOAA provided time-series measurements of wind speed, wind direction and SST. Data buoys were mostly located over the mid- or outer-shelf (Fig. 2). Component wind velocities, and anomalies in SST from the record-length estimate of the seasonal cycle, were computed at each buoy, and smoothed with a cosine-Lanczos filter with a half-power point of 40 h.

Coastal sea-level was obtained from tide gauges along the west coast (Fig. 2). A least-squares estimate for tidal constituents was removed from the hourly data at each tide station, and the static loading resulting from atmospheric pressure was estimated and removed using spatially interpolated atmospheric pressure from the NCEP reanalysis. In some time windows, linear interpolation across missing data had produced large erroneous residual sea levels; these were identified and removed. The mean, annual and semi-annual cycles were estimated and removed, using data from 1975 through 1995, as was a linear trend over the full data record. Anomaly data were then median filtered over 120 h.

3. Timing and alongshore extent: coastal SST and adjusted sea level

SST at the NDBC buoys show strong, positive temperature anomalies over the continental shelf during three periods in 1997 to mid-1998 (Fig. 3). During May and June 1997, anomalously warm SST was found over the mid-shelf from the Southern California Bight to the Washington coast; the maximum anomalies were weakest off central California, and strongest (>4°C) off northern California above San Francisco. This anomaly in SST showed no consistent evidence of alongshore propagation. Over this same period, large-scale analyses of Pacific SST anomalies (e.g. the US Navy's Optimum Thermal Interpolation System, OTIS, http://www.fnoc.navy.mil/PUBLIC/OTIS/otis.html) show a large positive oceanic temperature anomaly was developing offshore. At the end of July 1997 off southern California, anomalously warm SST returned over the shelf. A similar rise was seen farther north, but after some time delay (e.g. 13 days between Monterey, at 36.8°N, and the Columbia River, at 46.1°N). The strength of this anomaly off northern California exceeded that for the May–June event, with peak SST anomalies of >6°C at 40.7°N. This second anomaly endured about 2 months off southern California, while it was stronger and shorter in northern California above San Francisco. Finally, during October 1997 (southern California) to early November 1997, SST anomalies over the shelf increased and stayed positive into April 1998.

Atmospherically adjusted sea-level (ASL) anomalies (Fig. 4) showed a similar picture, with positive ASL anomalies, coherent along the whole coast, dominating from May 1997 through February 1998. The May–June warm event seen in the SST was clearly reflected in ASL. The largest ASL anomalies were seen in the north, off Oregon and Washington. This contrasts with the SST anomalies, which were strongest off northern California. This may reflect a difference in the vertical structure of the associated heat-content anomaly, or may reflect latitudinally-dependent cross-shore gradients in the size of the anomalies. At Newport (44.6°N), the maximum ASL anomaly for May exceeded 0.26 m. The second warm SST pulse, during July–September 1997 (Fig. 3), was not reflected clearly in the ASL anomalies (Fig. 4).

Positive ASL anomalies were strongest during September 1997 through February 1998. Average ASL anomalies over this period were 0.11 m at San Diego (32.7°N) and 0.18 m at Toke Point (46.7°N). These average ASL anomalies increased significantly with latitude (correlation 0.80), resulting in an anomalous, large-scale sea-surface slope of 4×10^{-8}. The extended positive ASL anomalies of this period ended abruptly in late February 1998 all along the coast; this should be contrasted with SST, where the anomalies persisted into April 1998. Farther from shore, altimetrically derived sea level also showed an abrupt end to positive anomalies in late February (Strub & James, 2002).

For the North American data shown in Fig. 4, correlations between sea level anomalies at San Diego and other latitudes were highest when the data were lagged in time, consistent with poleward propagation at 2.1 m/s (Fig. 5). This low-frequency propagation speed agrees with that determined by Enfield and Allen

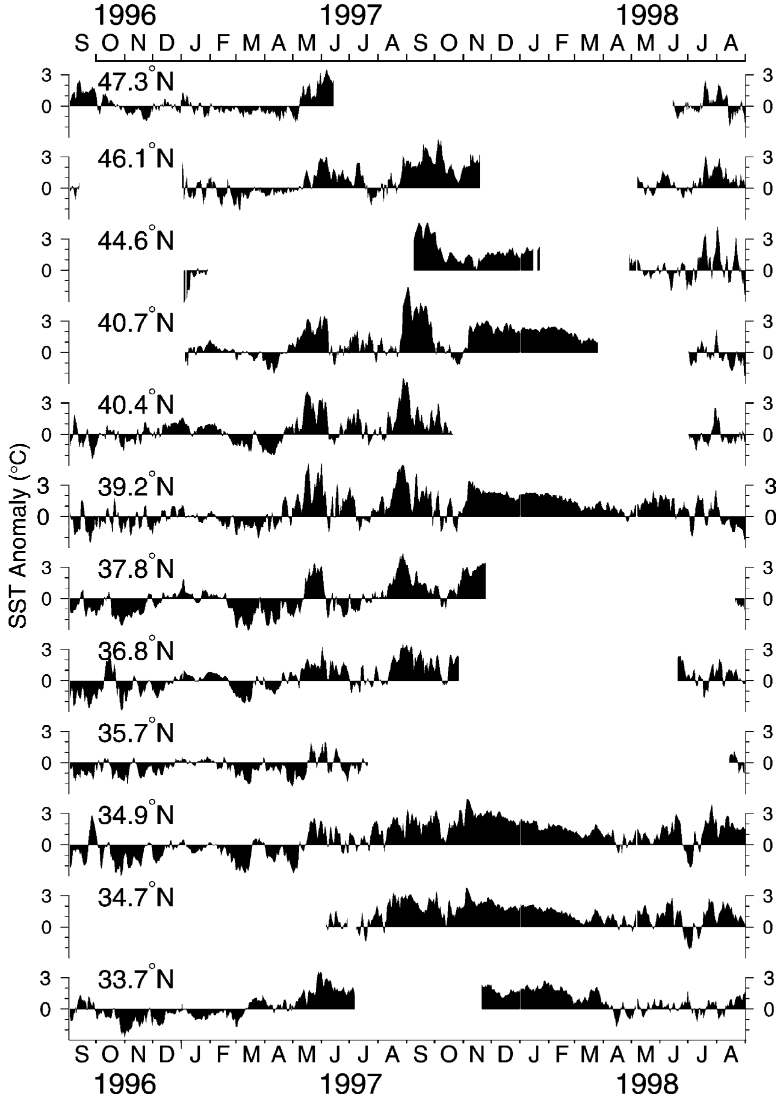

Fig. 3. Time-series of SST anomalies (°C) at series of latitudes along the US west coast, between September 1996 and August 1998, from NDBC buoy data, after removing the record-length estimate of the seasonal cycle, estimated at each buoy, and smoothing with a cosine-Lanczos filter with a half-power point of 40 h. Gaps in the plotted time series indicate missing data.

(1980) from a long time series of monthly mean data. Over larger scales, a 28 day lag gives maximum correlation between ASL anomaly data from Buenaventura, Columbia, and San Diego (Fig. 4); the corresponding poleward velocity is comparable, 2.3 m/s. These values are comparable to the speeds of first mode Kelvin waves (e.g. 2.5 m/s for N=4.0×10^{-3}/s and H=2000 m) or to equivalent coastal-trapped waves (Davis & Bogden, 1989; Ramp et al., 1997).

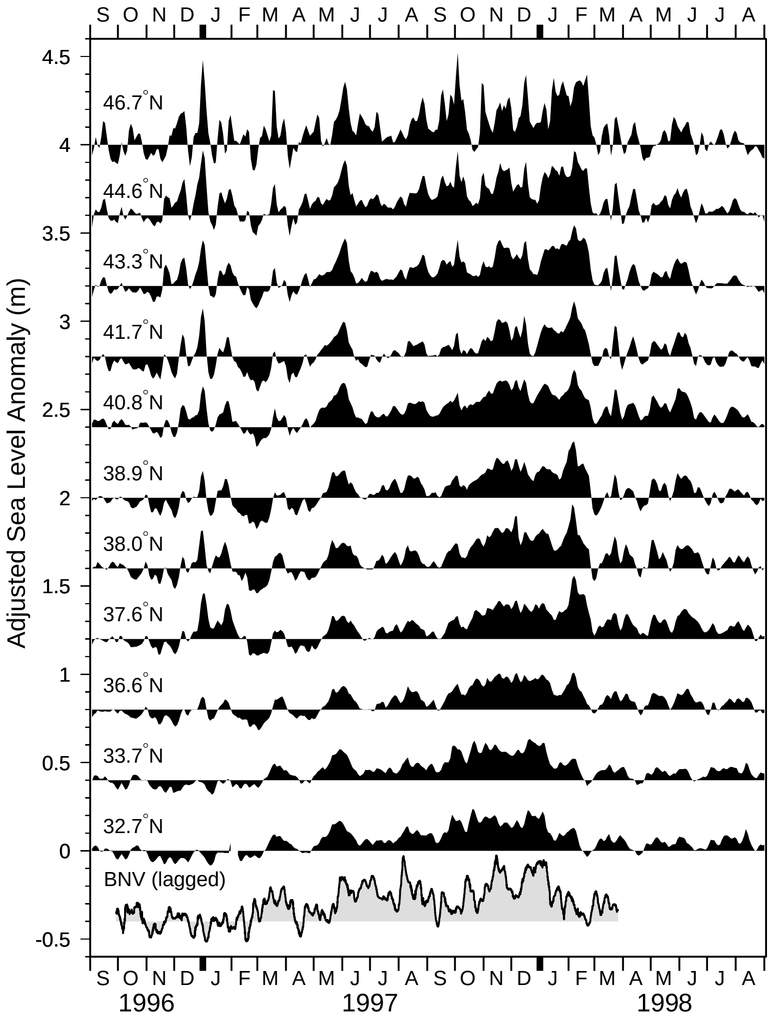

Fig. 4. Sea-level anomalies (meters) at coastal tide-gauge stations along the US west coast, between September 1996 and August 1998. Data were processed to remove tides, high-frequency fluctuations, the seasonal cycle, and secular trends, along with inverse-barometer response to atmospheric pressure. Similar data from a tide gauge at Buenaventura (BNV), Columbia (3.9°S, 77.1°W) are shown in gray, lagged by 28 days. For clarity, plots have been serially offset by 0.4 m.

4. Directly-measured currents

4.1. Time-series over the central Oregon shelf: mooring and HF radar

Time-series measurements of current profiles and near-bottom temperature over the continental shelf off Newport, Oregon during the 1997–98 El Niño were made at the NH-10 mooring (44.6°N, 124.3°W, 81 m bottom depth). The north-south currents over the shelf were generally poleward and weakly sheared vertically during the late fall and winter months, and generally equatorward, with equatorward vertical

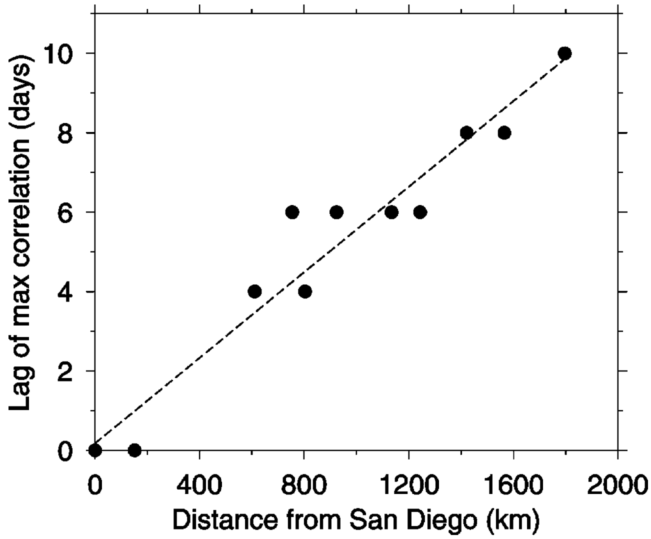

Fig. 5. Lags producing maximum correlation between adjusted sea level anomalies at San Diego and those farther north along the coast. Dashed line shows best fit, corresponding to a slope of 186 km/day, or 2.1 m/s. Correlations were taken over data from December 1996 through August 1998.

shear, following the spring transition to upwelling (Fig. 6a). This reflects the seasonal cycle described by Huyer and co-workers (Huyer et al., 1975; Huyer, Sobey, & Smith, 1979). Ocean temperatures were warmest during the winter, and coldest during the upwelling season (Fig. 6b).

Long-term averages of the currents are not yet available at this location. However, the difference between near-surface northward midshelf currents in 1997–98 and 1998–99 was strongly skewed during August through February, with ENSO-year northward currents exceeding next year currents 74% of the time. The mean difference over this period was 13.7 cm/s (Fig. 6c). If applied uniformly along the coast, this would result in anomalous northward displacement of more than 300 km per month, compared with the following year. On 22 February, the year-to-year anomaly in northward current abruptly reversed, and subsequently fluctuated around zero. This change in current anomaly corresponds closely in time with the sharp drop in sea-level anomaly observed at this latitude, and all along the coast (Fig. 4). The two large negative anomalies observed in late November and early December (Fig. 6c) were from transient, storm-driven northward currents in late 1998 (Fig. 6a).

Comparable northward accelerations have been found on the shelf during two other El Niños. Off Peru (Smith, 1983) found that average poleward shelf currents for comparable periods during and after El Niños were 23.2 versus 8.8 cm/s, 25.3 cm/s versus 4.4 cm/s off Peru for the 1976–77, 1982–83 events, respectively, and off Oregon (Huyer & Smith, 1985) found 13.0 versus 5.8 cm/s for the 1982–83 event.

The near-bottom temperature at the shelf mooring was consistently warmer by about 1°C in the ENSO year, beginning in September 1997 (Fig. 6d); this is consistent with hydrographic data at this location from November 1997 (Huyer et al., 2002). Anomalous upwelling in December 1998 (unrelated to ENSO) drove the December difference above 5°C.

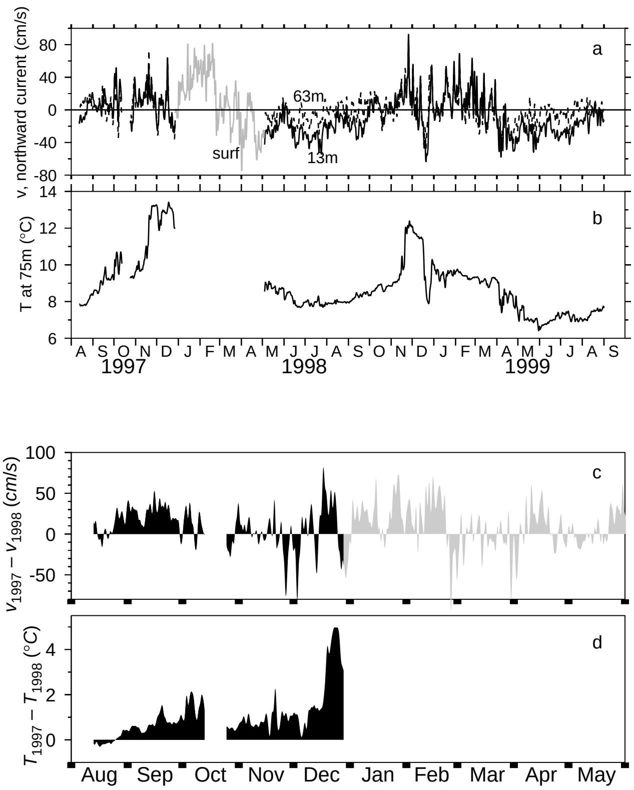

Fig. 6. Time series of (a) northward current and (b) temperature at 75 m, at the NH10 mooring (44.6°N, 124.3°W) in 81 m of water. In (a), current data are shown from 13 m and 63 m depth (heavy and dotted lines, respectively). A data gap from the end of December 1997 through April 1998 was filled with measurements from a coastal HF radar (shown in gray). (c) Difference between 13 m (or HF radar) currents in 1997–98 and 13 m currents in 1998–99; (d) as in (c), except for temperature at 75 m.

4.2. Shipborne ADCP

4.2.1. Three years on the NH line

In addition to continuous time-series measurements at fixed shelf moorings, direct current measurements are being made along seasonally-repeated transects with a ship-borne ADCP. Ship-based transects sampled between July 1997 and April 2000 are shown in Fig. 1 and listed in Table 1. The hydrography collected on these cruises is discussed by Huyer et al. (2002), who compare ENSO and non-ENSO periods from the present and also from earlier events.

Sections of northward current across the NH line (44.6°N) over 3 years are given in Fig. 7. A pressure-derived estimate of near-coastal wind forcing at 45°N, the upwelling (Bakun) index, is shown for this period in Fig. 8. By this measure, coastal winds at 45°N were near their seasonal average, and storms were of typical strength, during most of the El Niño. During February 1998, near the end of the episode, mean winds were more poleward than their seasonal average, but this also holds true for the La Niña February 1999.

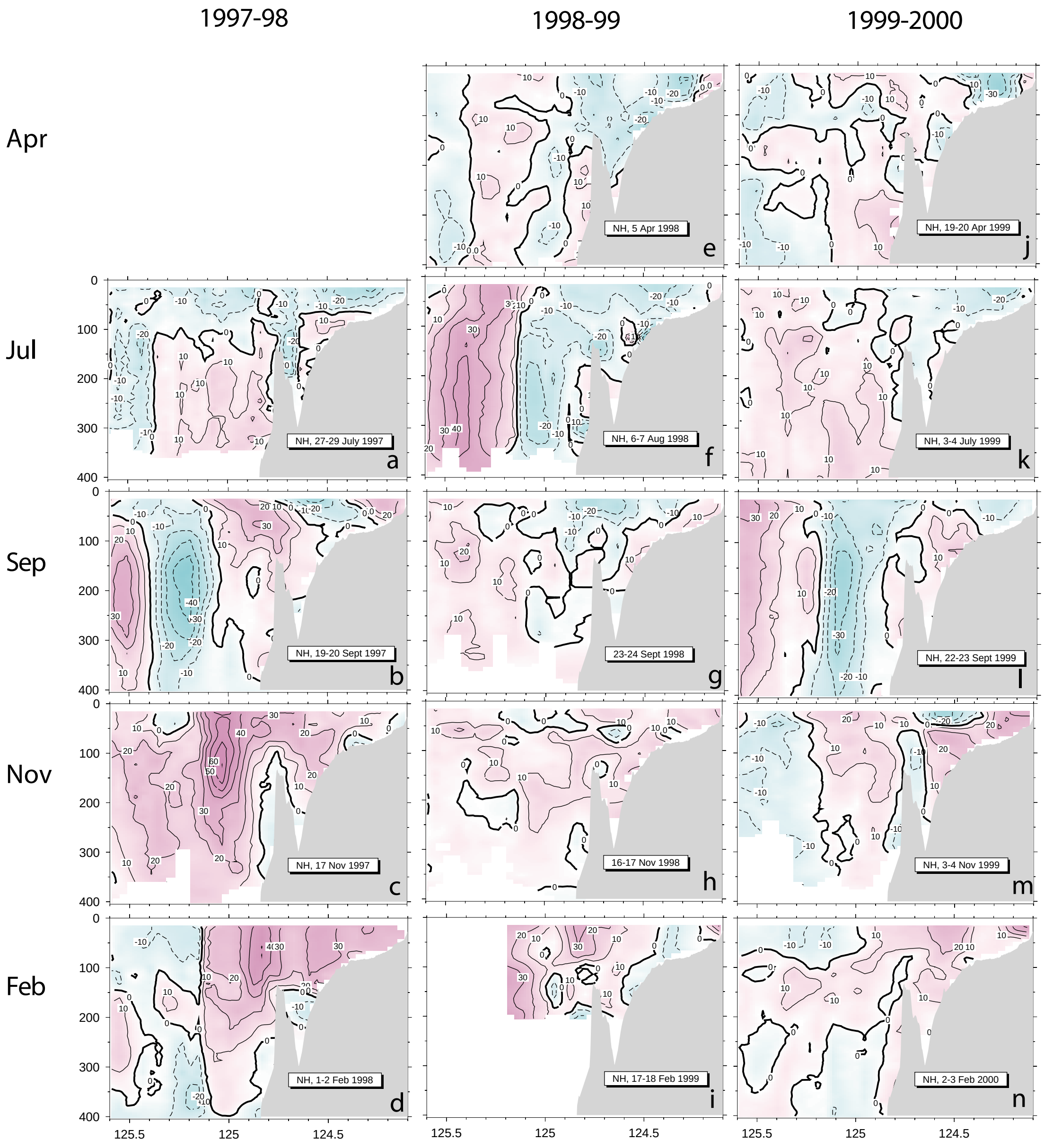

Fig. 7. Sections of meridional current across the NH sections on each cruise, versus depth in meters and offshore position in degrees of longitude. Northward (southward) flowing currents are colored magenta (cyan), and contours are drawn every 10 cm/s. Rows give the cruise month (April, July, September, November and February, corresponding respectively to early, middle, and late-upwelling, fall, and winter seasons); columns give the sampling year (1997–98, 1998–99, 1999–2000).

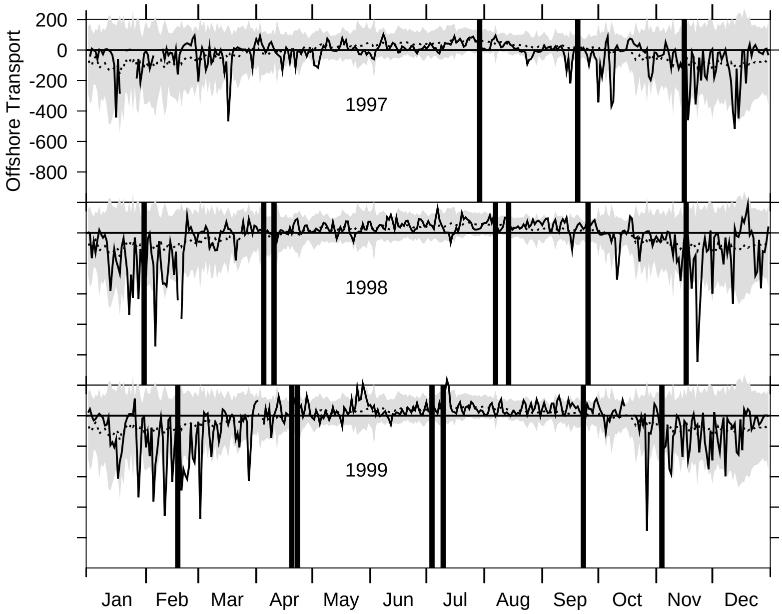

Fig. 8. The upwelling index, an estimate of the rate of offshore Ekman transport (m^3/s per 100 m of coastline), computed from geostrophically-estimated wind stress, at 45°N; 125°W, by Pacific Fisheries Environmental Laboratory of NOAA (http://www.pfeg.noaa.gov/products/current—products.html). This is taken to indicate the regional wind-stress. Dotted line indicates long-term mean, and shaded region indicates mean ±2 standard deviations. Times of Newport sections are indicated by vertical lines.

4.2.1.1. Continental shelf During the upwelling season, in spring through early fall, a surface-intensified equatorward current of moderate strength (10–30 cm/s) was usually observed over the continental shelf, centered close to the NH10 mooring, near 124.3–124.4°W (the upper three rows of Fig. 7). This is the coastal upwelling jet, arising in response to wind-forced upwelling of density surfaces over the shelf (Huyer et al., 1975). In the shallow waters inshore of the jet, a reversal to a northward current was repeatedly observed. Early in the season, the reversals were weak (10 cm/s) and located nearshore (out to 124.2°W), while later in the season, the nearshore reversals were stronger (September 1997) and more extensive. These poleward reversals co-varied with the winds, and are analogues of the 'wind relaxation events' observed off northern California (Kosro, 1987; Send, Beardsley, & Winant, 1987).

Most of the fall and winter sections off Newport (lower two rows of Fig. 7) are dominated by poleward flow east of 125°W. The strength and spatial structure in this flow varies considerably between sections, however, and there is even one section (November 1999) where strong equatorward flow is present over the shelf.

4.2.1.2. Continental slope and beyond Seaward of the shelf break, the current structure off Newport becomes more variable. In the vicinity of the shelf break, northward currents dominate, with a subsurface maximum—the local expression of the poleward undercurrent—typically seen early and mid-season. The depth of the subsurface maximum, when present, varies between about 100 and 350 m, and is often at or near the bottom over the slope. A particularly clear picture of the poleward undercurrent early in the upwelling season was obtained at different latitudes during 4–10 April 1998 (Fig. 9). The poleward undercurrent has been observed as a coherent feature along most of the west coast in summer (Pierce, Smith,

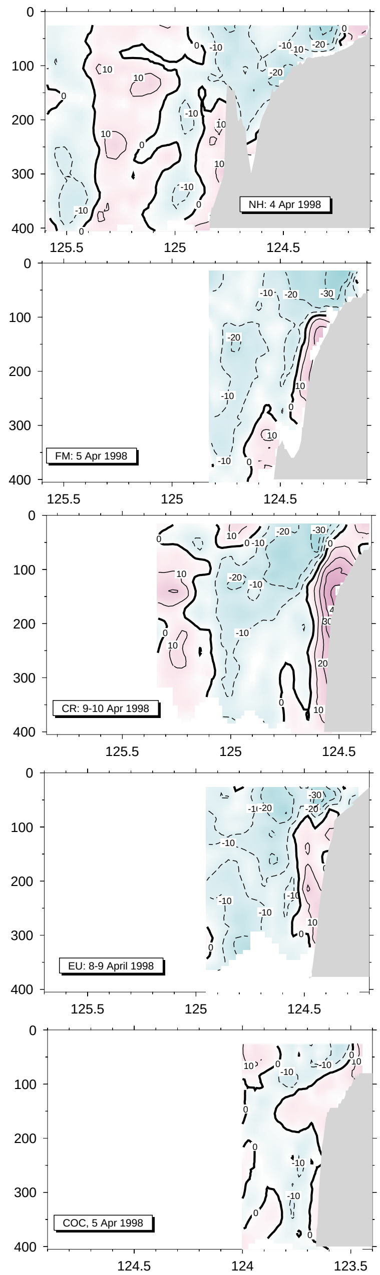

Fig. 9. Sections of meridional current across transects at the Newport Hydrographic (NH), Five Mile (FM), Crescent City (CR), Eureka (EU) and CODE Central (COC) Lines (see Fig. 1 and Table 1), during 4–10 April 1998. Northward- (southward-) flowing currents are colored magenta (cyan), and contours are drawn every 10 cm/s.

Table 2
Poleward volume transport, in Sverdrups (10^6 m^3/s), across the NH section in the region sampled by the shipborne ADCP (the third column is net poleward transport across the section, the fourth column is transport by poleward currents in the jet exceeding 0.1 m/s)

Cruise	Dates	Net poleward transport across the NH section (Sv)	Poleward transport by northward currents >0.1 m/s (Sv)
W9707B	28–30 July 1997		
W9709B	19–20 Sept 1997	0.0	0.7
W9711C	15–22 Nov 1997	5.3	5.3
W9801B	30 Jan–2 Feb 1998	2.6	3.1
W9804B	4–10 Apr 1998	−0.7	
W9808A	6–11 Aug 1998	1.9	
W9809A	24–26 Sept 1998	0.7	
W9811A	16–20 Nov 1998	1.6	1.0
W9902A	17–18 Feb 1999	1.0	1.0
W9904B	19–23 April 1999	−0.3	
W9907A	3–9 July 1999	1.4	
W9909C	22–27 Sept 1999	0.0	
W9911A	3–5 Nov 1999	0.4	1.0
W0002A	1–3 Feb 2000	1.0	2.3

Kosro, Barth, & Wilson, 2000) and appears to be a common feature of eastern boundary current systems globally (Neshyba, Mooers, Smith, & Barber, 1989).

4.2.2. ENSO and poleward jet

During the 1997–98 ENSO, fall and winter transects made at 44.6°N showed enhanced poleward flow in an upper-ocean current jet centered off the shelf break near 124.8° – 125.1°W (Figs. 7b, 7c and 7d). In September 1997, poleward shelf-break currents exceeded 30 cm/s; 0.7 Sv of poleward transport was carried by strong northward currents (>10 cm/s) within the jet, between 124.53°W and 125.2°W at depths between 17 and 400 m. By November 1997, the poleward jet was much more strongly developed. Peak speeds doubled, exceeding 60 cm/s, with the core of the jet centered near 125.0°W and 100 m depth. The strongest currents were found in the upper 200 m, over a width of about 25 km, although substantial poleward flow extended onto the shelf and to depths exceeding 350 m. Transport by strong poleward currents across the section was very high, reaching 5.3 Sv (Table 2).

In February 1998, poleward flow extended over most of the waters onshore of 125.1°W, and the poleward jet again was observed, with a surface-intensified core near 124.8°W. It was 20 km wide, had a core velocity exceeding 40 cm/s and extended to 150 m depth. Transport by strong northward currents in the section was 3.1 Sv.

The strong poleward flows observed in November 1997 and February 1998 had large alongshore extent, and were observed on all transects as far south as the CODE Central Line (Fig. 10). At some locations, poleward currents exceeded 50 cm/s. The core of the poleward flow was usually found near the continental shelf break. Poleward flow exceeding 20 cm/s typically extended to 300 m depth. Transports were 5.3, 3.5, 2.2, and 3.1 Sv across the NH, FM, CR, and COC sections, respectively, in November 1997, and were 2.6 and 1.8 Sv across the NH and FM sections, respectively, in February 1998.

As noted, wind forcing during the November 1997 section, as estimated from the upwelling index at 45°N, was comparable to that observed during other winter transects (Fig. 8). Winds estimated by Wecoma's officers indicated generally fair weather on the 6 day November 1997 cruise, interrupted by one overnight storm (Fleischbein et al., 1999), so that storm-driven forcing does not appear to be responsible for

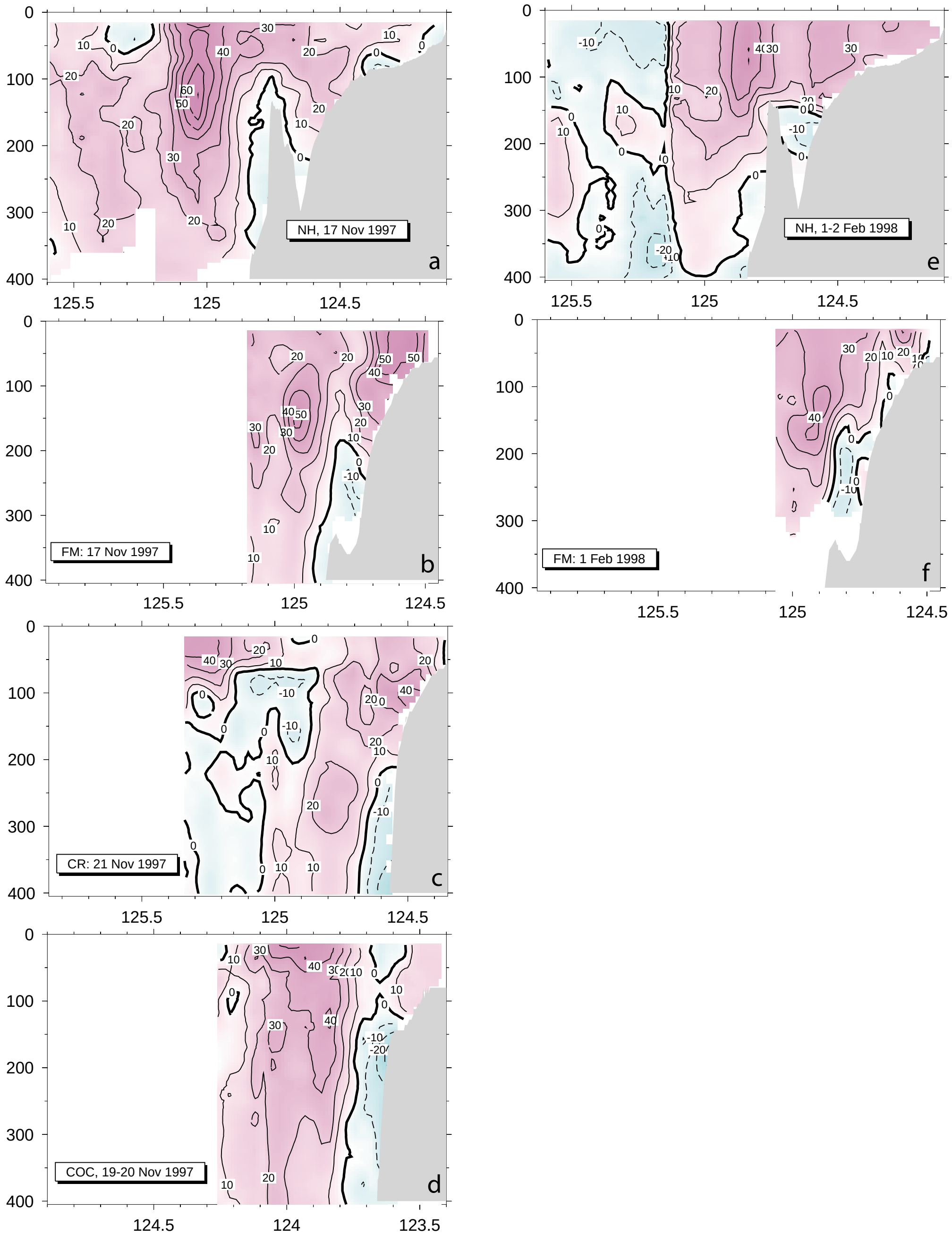

Fig. 10. As in Fig. 8, except for transects made during the El Niño. (a–d) 17–21 November 1997 and (e–f) 1–2 February 1998.

the stronger currents in November. During the February 1998 cruise, ship-based wind estimates exceeded 12 m/s during most of the sampling, but the forcing was similar in the other Februarys.

4.2.3. ENSO and equatorward undercurrent

An equatorward undercurrent appeared in each section collected during the height of the El Niño, in November 1997 and February 1998 (Fig. 10). This current was closely trapped near the bottom of the continental slope and shelf-break. The width of the feature in these sections was small, about 10 km. Core currents were strongest in the two southern sections, exceeding 20 cm/s, at depths comparable to, or somewhat deeper than, those associated with the better studied poleward undercurrent. In most sections, the equatorward undercurrent extended deeper than our observations. The fact that a similar current feature is observed in all sections increases the confidence that this is a real element of the low-frequency circulation, and not simply spatial aliasing of high-frequency variability.

Reports of equatorward undercurrents have been rare, possibly owing to the scarcity of high-resolution direct current measurements over the continental slope. A weakening of the mean poleward undercurrent during the fall and winter seasons has been observed from long-term current-meter records off Point Arena, California during 1981–82 (Huyer, Kosro, Lentz, & Beardsley, 1989) and 1992–94 (Kosro et al., 2002), and off Point Sur, California (Collins et al., 1996b). This appears to contrast with analyses from Central to Southern California from hydrographic data (Chelton, 1984; Lynn & Simpson, 1987), which generally indicate a spring-time minimum in subsurface poleward undercurrent flow. A winter reversal of the poleward undercurrent in the Pacific Northwest was predicted by Werner and Hickey (1983), based on their model of the effects of an imposed seasonal plus fluctuating longshore pressure gradient, estimated from historical hydrography and tide-gauge data. They predicted a peak equatorward current of 5 cm/s near 300 m depth for December 1980, in good agreement with their measurements of equatorward currents of 3 cm/s at that time.

The ADCP sections presented here indicate that the equatorward undercurrent was a rather narrow feature occurring near steep topographic changes, easily missed by geostrophic velocity estimates. In the three years sampled, the feature was most prominent during the ENSO winter of 1997–98, when it was strongest and present in all cross-shore sections.

We estimated anomalous slopes in ASL near Newport, Oregon from ASL anomalies, at Charleston, Oregon and Toke Point, Washington (Fig. 11). The anomalous ASL slope was positive (i.e. in the correct sense to contribute to an equatorward undercurrent) during most of the fall and winter of 1997–98, with a mean anomalous slope of 0.8×10^{-7} from June 1997 through February 1998 ($\pm0.4\times10^{-7}$ standard error of the mean). However, the anomalies during this period are not unusual, and are comparable to anomalies during the winters of 1996–97 and 1998–99. A similar result is obtained when a larger alongshore region is examined.

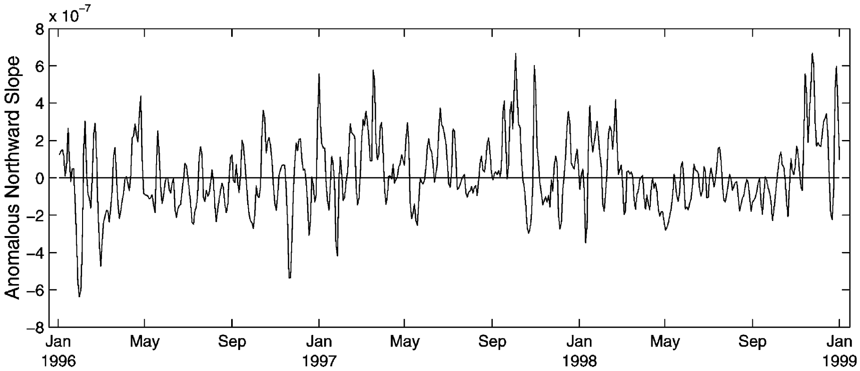

Fig. 11. Gradient in Adjusted Sea Level anomaly near Newport, Oregon, estimated from the difference between ASL at Toke Point, Washington (46.7°N) and Charleston, Oregon (43.3°N). Positive gradient corresponds to higher ASL anomaly in the north.

Clarke and Van Gorder (1994) used a model with bottom friction and a continental slope to study wave motions with periods of 2–5 years. Their model produced a near-bottom ‘ENSO jet’, which was narrow, bottom-intensified over the mid-slope and out-of-phase with the near-surface velocity, over depths between ~1000 and 2000 m; so that near-surface poleward flow would correspond to deep equatorward flow. The magnitudes of the modelled jet were comparable to those observed here, but the observed equatorward flow was shallower than predicted.

4.2.4. Recurrent anticyclonic eddies

A repeated feature of the slope circulation off Newport, observed in both ENSO and non-ENSO years, is worth noting here. An anticyclonic eddy offshore of 125°W re-occurred late in each of the three upwelling seasons, in September 1997, August 1998 and September 1999, centered near 125.4°W, 125.1°W and 125.2°W, respectively (Figs. 7b, 7f and 7l). The maximum eddy currents were subsurface, between 100 and 350 m, in depths normally associated with the poleward undercurrent. Maximum eddy currents exceeded 30 cm/s, with peak opposing currents separated by 27 km in 1997 and 1998; in 1999, the northward subsurface core appears to have been offshore of our sampling. The relative vorticity is strongest between the two velocity cores, where it exceeds $-0.4f$ in 1997 and 1999, and is approximately $-f$ (over <5 km) in 1998. The anticyclonic rotation of these eddies, together with the depth of their subsurface maxima, suggest that they originate in instabilities of the poleward undercurrent.

These anticyclones thus appear to be a regular feature of the circulation off central Oregon. A similar eddy in this region was described by Huyer et al. (1984), who tracked its motion northwestward during January to March 1978. They found its core to be warmer and more saline at the same density than surrounding waters; this was also true for the eddy observed in September 1997, though not for an eddy tracked in August 1998.

Similar subsurface-intensified anticyclones have been observed at depths corresponding to the California Undercurrent in hydrography off southern California (Lynn & Simpson, 1987, 1990), and in hydrographic and direct-current measurements off northern California (Kosro et al., 1991; Chereskin et al., 2000). Trajectories of subsurface floats placed in the California Undercurrent have confirmed the undercurrent as a source for these anticyclones (Collins et al., 1996a; Garfield et al., 1999).

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