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Enhanced southward flow over the Oregon shelf in 2002: A conduit for subarctic water

P. Michael Kosro

College of Oceanic & Atmospheric Sciences, Oregon State University, USA

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[1] Moored current measurements from the Oregon shelf during 1998–2003 are used to estimate time series of anomalous alongshore currents and pseudo-displacements, after accounting for the mean and seasonal cycle. From early January through mid-June, 2002, currents at 10 m were anomalously strong toward the south by an average 12 cm/s, producing an anomalous displacement of more than 1500 km over about 5 months. This may be compared with the finding by *Freeland et al.* [2003] that waters at the same latitude off Oregon, and off Vancouver Island, were anomalously cool and fresh at depths between 30 and 150 m, suggesting displacement from a more northern source. Anomalous displacements of several hundred kilometers were also found during at least three other periods in the record. Moored temperature measurements at the same location confirm that local waters were persistently cooler during March to October of 2002 than during the previous two years, with the strongest anomaly near 20 m. Coastal sea levels were lower than usual along the northwest coast during spring and early summer 2002, consistent with a southward current anomaly of large scale. Local winds near Newport did not show strong mean anomalies during this period. *INDEX TERMS:* 4215 Oceanography: General: Climate and interannual variability (3309); 4516 Oceanography: Physical: Eastern boundary currents; 4522 Oceanography: Physical: El Nino; 4283 Oceanography: General: Water masses; 4279 Oceanography: General: Upwelling and convergences. **Citation:** Kosro, P. M., Enhanced southward flow over the Oregon shelf in 2002: A conduit for subarctic water, *Geophys. Res. Lett.*, *30*(15), 8023, doi:10.1029/2003GL017436, 2003.

1. Introduction

[2] From hydrographic measurements off Oregon and Vancouver Island, *Freeland et al.* [2003] report that halocline waters of the northern California Current were anomalously cold during July 2002, by approximately 1°C, over the depth range of 30–150 m. They hypothesize that this cooling most likely is due to increased southward flow in the California Current and/or weaker northward flow in the Alaska and Davidson Currents during spring 2002, although other mechanisms were considered. Based on average meridional gradients of temperature and salinity in the pycnocline, they estimate that waters were displaced 500 km to the south of their normal summer positions.

[3] Here, an analysis of continuous moored current and temperature measurements over the Oregon shelf from this period reveals that sustained enhanced southward flow was present at speeds more than sufficient to produce such displacements. Because these measurements are continuous and of long duration, departures from seasonal norms can be identified, and the times of onset, duration, and average or peak strength for significant anomalies can be determined with less time aliasing than from many other techniques.

2. Measurements

[4] A long-term mooring site on the Oregon shelf was established in August 1997, near 44°38.8′N, 124°18.3′W, at 81 m water depth, as part of the GLOBEC Long-Term Observation Program (LTOP). This location is less than 1 km south of the Newport Hydrographic Line (44°39.1′N), along which the anomalous halocline water was first identified. The nearest repeat hydrographic station is NH10. Upward-looking acoustic Doppler profilers have been used to measure vertical profiles of current velocity there, with a 2 m and 4 m vertical sampling interval using Sontek 500 kHz and 250 kHz profilers, respectively. The record has short gaps for instrument turnaround (usually less than a day), and one large gap from Dec 30, 1997 to May 1, 1998. Currents were processed to hourly averages, low-pass filtered using a cosine-Lanczos filter with a 40-hr half-power point, and then resolved into alongshore (positive toward 22°T) and cross-shore (112°T) components, based on an average direction for the principal components in the mid water column. Beginning in April 2000, a second mooring was added nearby to measure temperature and salinity, usually at 11 and 4 depths respectively. Time series of pressure and fluorescence were also measured at one depth each on the mooring.

3. Analysis

[5] The time-series of low-pass filtered alongshore current at 10 m depth, for the 5-year period of continuous record from May 1998 to March 2003, is characterized by an equatorward mean advection and a seasonal cycle, together with higher frequency variability (Figure 1a). An estimate of the average seasonal cycle was made by fitting the alongshore and cross-shore current at each depth to a mean plus an annual and semi-annual cycle [*Strub et al.*, 1987]; at 10 m, the annual mean currents are (−11.4, 0.1) cm/s and the seasonal fits have an amplitude of approximately (22, 3) cm/s for the alongshore and cross-shore components, respectively, accounting for (41%, 9%) of the variance in each (Figure 1a).

[6] The anomaly of the measured alongshore current at 10 m (residual after removing the mean and seasonal cycle, Figure 1b) has energy at many time scales; its spectrum (not shown) is pink, with moderate peaks near 90- and 40-days,

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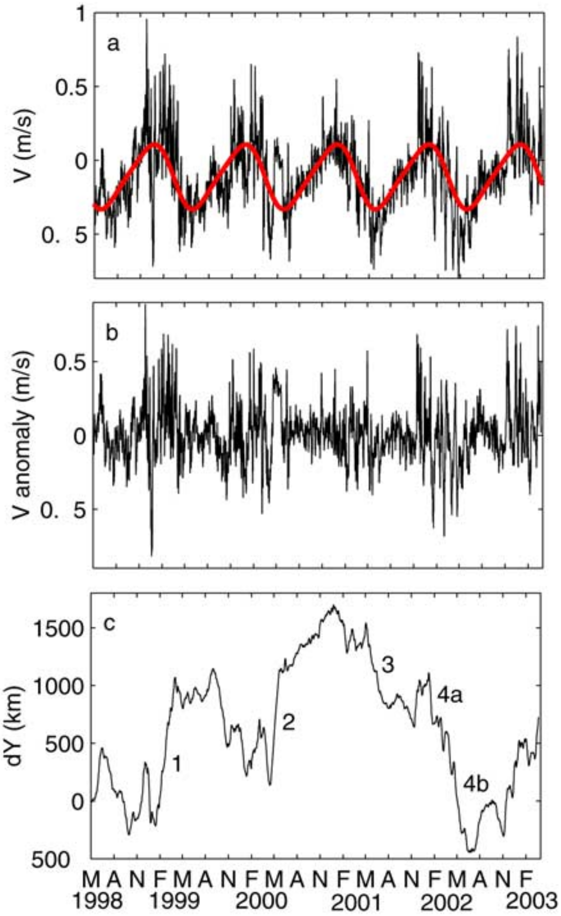

Figure 1. (a) Alongshore current at 10 m at the NH-10 mooring (44°38.8′N, 124°18.3′W, 81 m water depth). Horizontal tick marks are once every 3 months (February, May, August, and November). Currents have been low-pass filtered and rotated 22° clockwise. A fit to the mean plus seasonal cycle is shown. (b) Anomaly in alongshore current, after removing the estimate for mean and seasonal cycle. (c) Alongshore pseudo-displacement, obtained by integrating the velocity anomaly over time. Periods of sustained anomalous displacement are indicated.

and an integral time scale [*Davis*, 1976] of 4.6 days. The standard deviation of the alongshore current anomaly time-series at 10 m is 17.9 cm/s.

[7] By integrating the anomalous alongshore current in time, an equivalent anomalous pseudo-displacement may be computed (Figure 1c). This is the analogue of one component of a progressive vector diagram, and comes with the same caution (e.g., true displacements could only be computed if the velocity field were known at all locations, not simply at the mooring). Only the change in the displacement between any two times is meaningful; the absolute value at any time depends on the starting time. Extended periods of anomalous poleward currents can be seen during (1) January 13 to March 31, 1999 and (2) April 18 to May 22, 2000, and anomalous equatorward currents dominate during the periods (3) May 3 to July 12, 2001 and (4) January 9 to June 12, 2002.

[8] Table 1 summarizes the anomalous alongshore advection at 10 m during the four periods noted above. Durations were 76, 34, 70 and 154 days, with anomalous alongshore displacements of 1250, 970, −700 and −1550 km and mean anomalous alongshore currents of 19, 33, −11 and −12 cm/s respectively, all of which differed from zero by at least 2.5 standard errors.

4. Discussion

[9] The anomalous advection during 2001 and 2002, the two years preceding the recognition of the subarctic water mass intrusion, clearly indicates the overall dominance of southward advection above the record-length estimate of the seasonal norm, by an average of 4.6 cm/s over the 18 months beginning in January 2001. The enhanced advection was stronger in 2002 than in 2001 (Figure 1c).

[10] The 2002 southward event, (4), is best described as two shorter events—(4a) during January 9–24, 2002 (14.7 days, −439 km, −34.6 cm/s), and (4b) March 30–June 12, 2002 (74.3 days, −976 km, −15.2 cm/s)—with little net displacement occurring during February and March 2002 (Figure 1c). The vertical structure of the anomaly also differs between the two shorter events. During the winter period 4a, the equatorward anomaly is barotropic, while during the spring period 4b it is surface intensified (Figure 2), with nearly linear anomalous shear of $-0.26 \times 10^{-2}\ s^{-1}$ in the upper water column between 10 m and 48 m, corresponding at 10 m to a 56% increase in current strength above the seasonal average of −27.1 cm/s for that 74-day period. The vertical structure of the anomalies reflect the seasonal means of the currents, which tend to be depth-independent in winter following mixing and downwelling, and sheared in spring/summer following upwelling [*Huyer et al.*, 1975; *Kosro*, 2003, in preparation].

[11] These sustained anomalous currents are surprisingly large. Event 4, which immediately precedes the striking water mass measurements of July 2002 [*Freeland et al.*,

Table 1. Anomalous Advection During Identified Periods

Period	Start	End	Duration (days)	⟨vanom⟩ (cm/s)	std error (cm/s)	dYanom (km)
1	Jan 13, 1999	Mar 31, 1999	76	19.0	4.4	1250
2	Apr 18, 2000	May 22, 2000	34	33.2	6.6	970
3	May 03, 2001	Jul 12, 2001	70	−11.5	4.6	−693
4a	Jan 09, 2002	Jan 24, 2002	15	−34.6	9.9	−439
4b	Mar 30, 2002	Jun 12, 2002	74	−15.2	4.5	−976

Statistics of the anomalous advection associated with the periods identified in Figure 1c. Start and end times were identified subjectively from the figure. The mean of the anomalous alongshore velocity over this period, $\langle v_{anom} \rangle$, and the equivalent anomalous alongshore pseudo-displacement, dY_{anom}, were computed. The degrees of freedom for the standard error of the mean anomaly were estimated as the square root of the number of integral time scales τ = 4.6 days.

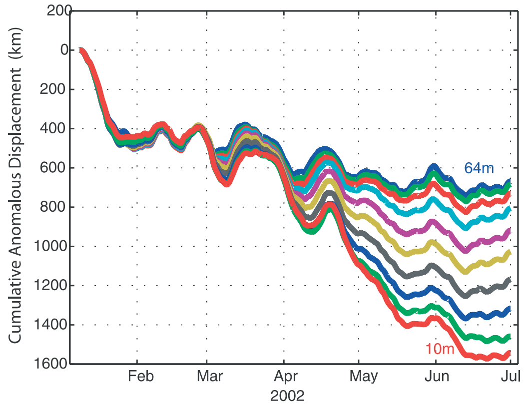

Figure 2. Anomalous pseudo-displacement during event 4, for depths ranging from 10 m to 64 m. Adjacent curves are separated by 6 m vertically.

2003], had current anomalies comparable in magnitude and duration, but opposite in direction, to those seen during the 1997–98 El Niño [*Kosro*, 2002].

[12] Temperatures were nearly always cooler at this shelf location in spring and summer of 2002 than during either 2001 or 2000 (Figure 3a). Temperature was measured at common depths during April 12 through June 12 of 2000, 2001 and 2002 on a mooring less than 1 km away. Average temperatures were colder at all depths during 2002 than during the same period in 2001 or 2000 (Figure 3b). The largest differences were near 20 m (−1.7°C for 2002–2000; −0.8°C for 2002–2001), smaller but still negative with increasing depth (−0.4°C and −0.1°C at 71 m for 2002–2000 and 2002–2001, respectively). Salinity, measured at fewer depths, did not provide robust differences.

[13] Local wind forcing was not strongly anomalous during period 4b of enhanced southward advection and cooler shelf temperatures. Anomalies in measured winds at NDBC buoy 46050 (44°37.3′N, 124°31.7′W, or 18 km west of the mooring) were computed by removing a mean and seasonal fit based on the data from 1992–2002. The mean anomaly and standard error for each period above was (1) 4.4 ± 0.9 m/s, (2) 2.4 ± 0.7 m/s, (3) −1.6 ± 0.7 m/s, and (4b) −1.3 ± 0.9 m/s (the buoy was not working during period 4a).

[14] While the anomalous wind forcing was significantly non-zero during the first 3 periods, and in the expected direction, the mean wind anomaly during the period 4b, immediately preceding the finding of the cool anomaly, was less than 2 standard errors from zero, indicating that it is not significant at the 95% confidence level. Similarly, examination of the PFEL (Bakun) upwelling index at 45°N, 125°W fails to show a strong, persistent local anomaly during period 4b. At larger scales, however, *Murphree et al.* [2003] argue that anomalies in wind stress and wind stress curl accelerate the eastward inflow to, and the equatorward flow of, the California Current system during this period.

[15] Anomalies in alongshore currents are likely to coincide with anomalies in coastal sea level, due to the largely geostrophic balance of the cross-shore momentum equation [*Huyer*, 1980]. Anomalies in coastal sea level were computed by removing long-term and seasonal averages from low-pass-filtered, atmospherically corrected tide-gauge data from stations along the U.S. west coast (Figure 4), as in earlier work [*Kosro*, 2002]. Coastal sea level is anomalously low during much of the winter and spring of 2002 over a long stretch of the west coast, particularly north of Point Reyes, CA (38.0°N), with the springtime anomalies being largest in the north. At Newport (44.6°N), over the length of the current record, the anomalous currents at 10 m are significantly positively correlated with the anomalous sea level, with a correlation coefficient of 0.75; the regression is

$$V_{anom}(m/s) = 1.57\,s^{-1} * H_{anom}(m) - 0.01\,m/s.$$

[16] However, the mean sea level anomaly during period 4b was only −0.058 m, or about 57% of the value predicted by the regression.

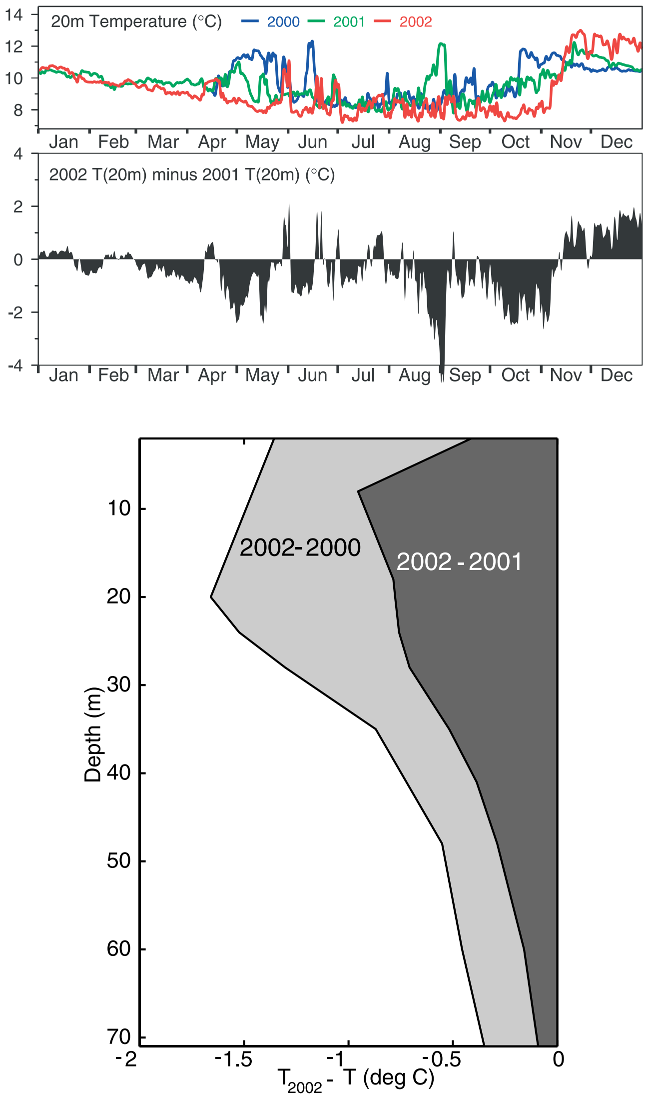

Figure 3. (a) Temperature at 20 m measured on a mooring less than 1 km away from the current-meter mooring. (upper panel): Temperature time series for each of the three years of data, beginning in 2000. (lower panel): Time series of the temperature difference, 2002 minus 2001, at 20 m, showing the persistence of cooler temperatures during spring and summer, 2002. (b) for the common time period April 12 through June 12, average difference of year 2002 from two preceding years, at all depths measured.

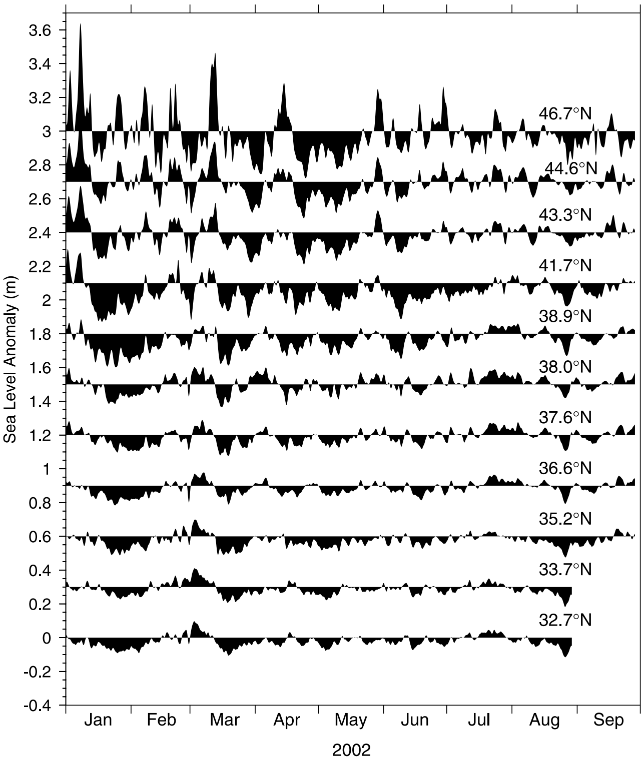

Figure 4. Sea-level anomalies (meters) at coastal tide-gauge stations along the US west coast, between January and September 2002. Data at each station were processed independently to remove tides, high-frequency fluctuations, the seasonal cycle, and secular trends, along with inverse-barometer response to atmospheric pressure [*Kosro*, 2002]. For clarity, plots have been serially offset by 0.4 m.

[17] An interannual change in the timing of the spring transition alone does not appear to be sufficient to produce these anomalies.

[18] These measurements are well resolved in time and in the vertical, but they are for flow only at a single location on the Oregon shelf. Measurements in other locations suggest that a similar enhancement of equatorward flow was seen there. *Strub and James* [2003] use altimeter measurements to document enhanced large-scale equatorward flow into and within the California Current, offshore of the continental shelf. *Barth* [2003] compares drifter releases from the same season in different years off central Oregon to support the finding of enhanced equatorward flow in the upwelling jet there during April 2002. Off southern California, *Bograd and Lynn* [2003] report anomalous hydrographic conditions consistent with those seen off Oregon and British Columbia. Concurrent observations also indicate enhanced nutrients and increased primary production from British Columbia to northern California during the summer of 2002 [*Thomas et al.*, 2003; *Wheeler et al.*, 2003].

[19] Time-series measurements of currents and temperature at midshelf off Newport, Oregon, have shown that the spring and summer of 2002 had anomalously strong equatorward flow, most intense near the surface, averaging 12 cm/s at 10 m over a period of 5 months, accompanied by anomalously cold water at all depths, during the period immediately preceding the measurement (in July 2002) of anomalously cool, fresh halocline waters off Oregon and Vancouver Island.

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References

Barth, J. A., Anomalous southward advection during 2002 in the northern California Current: Evidence from Lagrangian surface drifters, *Geophys. Res. Lett.*, 10.1029/2003GL017511, 2003.

Bograd, S. J., and R. J. Lynn, Anomalous subarctic influence in the southern California Current during 2002, *Geophys. Res. Lett.*, 10.1029/2003GL017446, 2003.

Davis, R. E., Predictability of sea surface temperature and sea level pressure anomalies over the North Pacific Ocean, *J. Phys. Oceanogr.*, *6*(3), 249–266, 1976.

Freeland, H. J., G. Gatien, A. Huyer, and R. L. Smith, Cold halocline in the northern California Current: an invasion of subarctic water, *Geophys. Res. Lett.*, *30*(3), 10.1029/2002GLO16663, 2003.

Huyer, A., The offshore structure and subsurface expression of sea level variations off Peru, 1976–1977, *J. Phys. Oceanogr.*, *10*(11), 1755–1768, 1980.

Huyer, A., R. D. Pillsbury, and R. L. Smith, Seasonal variation of the alongshore velocity field over the continental shelf off Oregon, *Limnol. Oceanogr.*, *20*(1), 90–95, 1975.

Kosro, P. M., A poleward jet and an equatorward undercurrent observed off Oregon and northern California, during the 1997–98 El Niño, *Prog. Oceanogr.*, *54*(1–4), 343–360, 2002.

Murphree, T., S. J. Bograd, F. B. Schwing, and B. Ford, Large scale atmosphere-ocean anomalies in the northeast Pacific during 2002, *Geophys. Res. Lett.*, 10.1029/2003GL017303, 2003.

Strub, P. T., and C. James, Altimeter estimates of anomalous transports into the California Current during 2000–2002, *Geophys. Res. Lett.*, 10.1029/2003GL017513, 2003.

Strub, P. T., J. S. Allen, A. Huyer, R. L. Smith, and R. C. Beardsley, Seasonal cycles of currents, temperatures, winds, and sea level over the Northeast Pacific continental shelf: 35 degree N to 48 degree N, *J. Geophys. Res.*, *92*(C2), 1507–1527, 1987.

Thomas, A. C., P. T. Strub, and P. Brickley, Anomalous satellite-measured chlorophyll concentrations in the northern California Current in 2001–2002, *Geophys. Res. Lett.*, 10.1029/2003GL017409, 2003.

Wheeler, P. A., A. Huyer, and J. Fleischbein, Cold halocline, increased nutrients and higher productivity off Oregon in 2002, *Geophys. Res. Lett.*, 10.1029/2003GL017395, 2003.

P. M. Kosro, College of Oceanic & Atmospheric Sciences, Oregon State University, USA. (kosro@oce.orst.edu)