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Anomalous Southward Advection During 2002 in the Northern California Current: Evidence from Lagrangian Surface Drifters

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[1] Equatorward velocities in the upwelling jet of the northern California Current were 0.05–0.06 m s^{-1} faster in spring and summer 2002 than on average over 1998–2002. This result is based on a five-year data set of surface drifters released across the continental margin off central Oregon (44.65°N) during April and July of each year. At this speed, anomalous water displacements of over a degree of latitude can occur in 20–25 days. Given a source of cold, Subarctic water to the north, this anomalous southward displacement is a plausible explanation for the cold, nutrient-rich halocline water observed off Oregon during the summer of 2002. This interannual variability in the northern California Current and its implications for the ecosystem response, i.e., increased primary productivity, may be contrasted with interannual variability of the opposite sign - increased poleward velocity, warmer temperatures and decreased productivity - observed in this same region during El Niño years. *INDEX TERMS:* 4516 Oceanography: Physical: Eastern boundary currents; 4215 Oceanography: General: Climate and interannual variability (3309); 4528 Oceanography: Physical: Fronts and jets. **Citation:** Barth, J. A., Anomalous Southward Advection During 2002 in the Northern California Current: Evidence from Lagrangian Surface Drifters, *Geophys. Res. Lett.*, *30*(15), 8024, doi:10.1029/2003GL017511, 2003.

1. Introduction

[2] A 5-year surface drifter data set is used to compare the strength of equatorward flow off the Pacific Northwest coast during 2002 to the average conditions over 1998 to 2002. One motivation for this study was the finding of *Freeland et al.* [2003] that unusually cold water was found in the halocline of the northern California Current (CC) during 2002 and their suggestion that this water was of Subarctic origin. The surface drifters provide a unique Lagrangian measure of the displacement of water parcels in the northern CC.

[3] During the Global Ecosystems Dynamics Northeast Pacific (GLOBEC NEP) Program, surface drifters were released at regular intervals at several cross-shelf locations off Newport, Oregon (44.65°N). The drifter deployment locations extend across the continental shelf and slope over a distance comparable to other measurements made on the Newport Hydrographic (NH) line (44.65°N) [*Huyer et al.*, 2002]. The Lagrangian surface velocities complement Eulerian velocities measured at a single mid-shelf mooring located 10 (18.5) nautical miles (km) offshore during the same time period [*Kosro*, 2003]. By covering a larger area, the drifters extend the single-point moored velocity observations and provide a link to the larger scale altimeter-derived [*Strub et al.*, 2003] and model-derived [*Murphree et al.*, 2003] surface velocities. Conversely, drifter velocities along a Lagrangian pathway can be considered anchored geographically through comparison with the mid-shelf mooring. From a temporal point-of-view, the drifter data provide an average measurement of surface velocity to complement the "snapshot" geostrophic and shipboard acoustic Doppler current profiler velocities made along the NH line [*Huyer et al.*, 2002; *Freeland et al.*, 2003; *Kosro*, 2002]. In this sense, they average over the short-term influence of local wind forcing and coastal trapped waves [*Allen*, 1980].

[4] During spring and summer, time-averaged surface velocities over the continental shelf and slope in the northern CC off the Pacific northwest are equatorward [*Huyer et al.*, 1978]. Velocities are strongest in the core of an equatorward upwelling jet with its axis located over the mid-shelf, 80–100 m depth located approximately 15 km offshore off Newport, Oregon [*Huyer et al.*, 1978]. Summertime average near-surface velocities obtained from moored observations are up to 0.35 m s^{-1} in the core of the upwelling jet. The alongshore flow is correlated for long distances (100 km or more) along the coast [*Kundu and Allen*, 1976]. Nearshore reversals, i.e. poleward flow, can occur in response to wind relaxations or periods of northward wind [*Kundu and Allen*, 1976], but the region of reversed flow is generally inshore of the drifter data used here because the closest deployment to the coast was 18.5 km offshore.

[5] Mean surface flow offshore of the continental slope in the northern CC is equatorward and weak (<0.1 m s^{-1}) [*Hickey*, 1979]. Mesoscale meanders and eddies are associated with the relatively strong mean equatorward upwelling jet over the continental shelf and slope and embedded in the weaker equatorward surface flow in the adjacent deep ocean. Meanders result from hydrodynamic instability and flow-topography interaction and have horizontal wavelengths of 20 to several hundred kilometers [*Barth*, 1989, 1994]. Eddies in the northern CC are usually found offshore of the equatorward upwelling jet and can be either cyclonic [*Barth and Smith*, 1998] or anticyclonic [*Huyer et al.*, 1998] and range in diameter from 50–90 km. With rotational flow speeds of 20–40 km d^{-1}, this results in a 4–15 d time scale for complete circulation around an eddy.

[6] A single realization of wind-event timescale surface currents in this region from a Lagrangian point-of-view was reported by *Stevenson et al.* [1974]. *Barth et al.* [2000] and *Barth and Smith* [1998] used surface drifters deployed over

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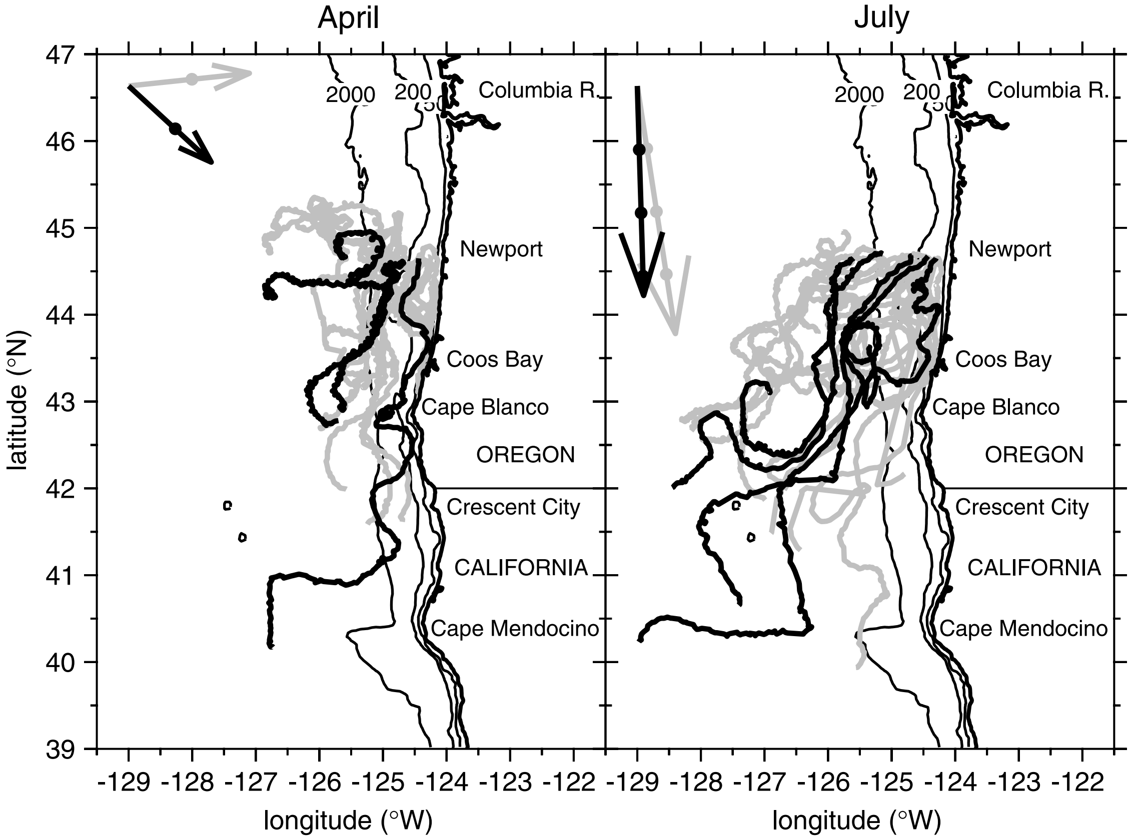

Figure 1. Drifter trajectories over 30 days originating from five cross-shelf locations from deployments in April (left) and July (right). Trajectories from 1998–2001 are in gray and those from 2002 are black. Average wind stress vectors over 30 days from NOAA NDBC buoy 46050 37 km offshore of Newport for 1998–2001 (gray) and 2002 (black) are shown in the upper left of each panel. Tics along the wind stress vectors are at 0.01 N m^{-2} intervals. Isobaths in meters.

the shelf off southern Oregon to describe the separation of a coastal upwelling jet from the coast. The surface circulation off the Pacific Northwest coast during wintertime, a period of strong northward flow in the Davidson Current, was described using surface drifters by *Austin and Barth* [2002].

2. Data and Methods

[7] During April, July and September of each year from 1998 to 2002, five drifters were released in a cross-shelf line at 44.65°N at 10 (18.5), 15 (27.8), 25 (46.3), 45 (83.3) and 65 (120.4) nautical miles (km) offshore. The drifters were deployed as part of the GLOBEC NEP Long-Term Observation Program (LTOP) during occupations of the NH Line [*Huyer et al.*, 2002]. The WOCE-standard, holey-sock drifters are drogued at 15 m and are tracked via satellite [*Niiler et al.*, 1995]. At this latitude, fixes are obtained roughly 9–12 times per day. The drifters are designed such that they slip less than 0.01 m s^{-1} in 10 m s^{-1} wind speed [*Niiler et al.*, 1995].

[8] Drifter fixes were used to compute the east-west and north-south displacement and speed over 15, 30 and 45 d periods starting from the time of each drifter's deployment. An average displacement speed and its standard deviation was computed for each cross-shelf location and for each of the 15, 30 and 45 d periods by using all the data from 1998 to 2002. These averaging intervals were chosen to be longer than the typical wind event time scale (2–10 d) and the period of long, coastal trapped waves previously observed in this region [4–14 d; *Allen*, 1980]. By temporally averaging it is also hoped to minimize the influence of meander and eddy motions in the alongshore coastal upwelling jet which have time scales of 1–15 d [*Barth*, 1989].

[9] Offshore surface drifter velocities are compared with an estimate of the offshore wind-driven Ekman transport due to alongshore wind stress distributed over a 20-m deep near-surface layer. Winds are obtained from the NOAA NDBC buoy 46050 located 37 km offshore of Newport, Oregon, and wind stress is calculated following the method of *Large and Pond* [1981].

3. Results

[10] Drifter trajectories over 30 days from the time of deployment at each cross-shelf location off Newport in spring (April) and summer (July) show the generally equatorward mean flow and the meandering and eddying of the coastal upwelling jet (Figure 1). The offshore component of the surface flow, stronger in July, is due in part to offshore Ekman transport under southward wind stress during this time (Figure 1). During April the average wind stress for 1998–2001 has a small north-south component, consistent with fluctuating winds during spring. Southward displacements are stronger in July when the average southward wind stress is also stronger. During 2002, equatorward trajectories are generally longer than those during the

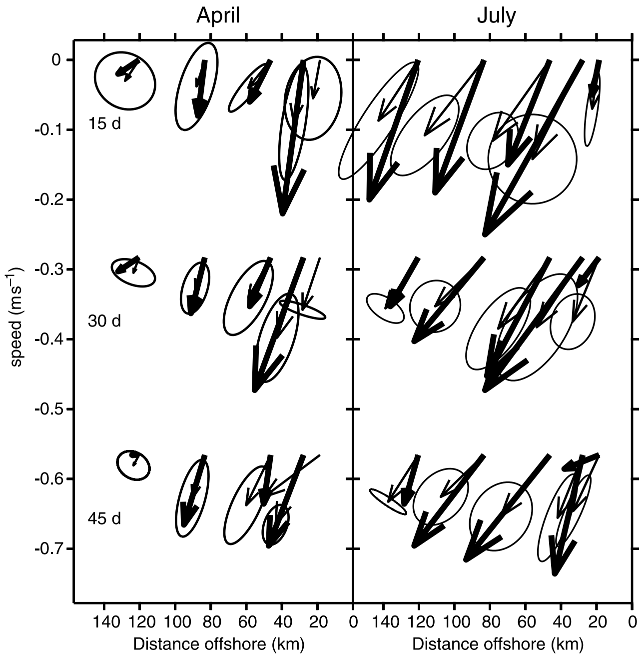

Figure 2. Drifter velocity vectors from five release locations across the shelf at 44.65°N, averaged over 15, 30 and 45 d (top, middle, bottom) starting in April (left) and July (right). Thin vectors with standard deviation ellipses represent averages over all deployments from 1998 to 2002. Bold vectors are for 2002. Note that the most inshore drifter deployed in April 2002 grounded after just 9 days so no bold vector is plotted for that time and place. North is toward the top of the figure.

previous four years. The average wind stress in April 2002 has a large southward component relative to the 1998–2001 period, but southward wind stress in July 2002 is not anomalously large.

[11] The mean and standard deviation of the displacement speed for 1998–2002 for each cross-shelf location computed over 15, 30 and 45 d intervals are plotted in Figure 2 (thin vectors and ellipses). The mean displacement speeds are equatorward and offshore, the latter having a contribution from cross-shelf Ekman transport in the surface layer under southward wind stress during these times. Mean velocities are in excess of 0.1 m s^{-1} during April in the center of the upwelling jet and reach 0.14 m s^{-1} during July, later in the upwelling season. The mean equatorward flow is stronger, occupies a larger region offshore and is more well organized in July compared with April. There is also a stronger offshore component to the surface flow in July, again in response to the strong wind forcing during this time. While cross-shelf Ekman transport during April is near zero, offshore velocities in a 20-m deep Ekman layer in July average 0.08 m s^{-1}, a substantial fraction of the observed offshore displacement speeds.

[12] Velocity vectors from 2002 (bold vectors, Figure 2) can be compared with the 1998–2002 mean velocities and standard deviations. In many places, in particular in the core of the upwelling jet (the middle three of the five drifter deployment locations, i.e. 27.8–83.3 km offshore), the flow is anomalously equatorward in 2002. The anomaly at 27.8 km offshore in the jet in April ranges from 0.03–0.13 m s^{-1}, exceeding one standard deviation of the mean for each averaging interval. The anomalous equatorward flow in April averaged over deployments at 27.8, 46.3 and 83.3 km offshore are 0.06, 0.04 and 0.02 m s^{-1} for the 15, 30 and 45 d period, respectively. In July, the surface flow is even more anomalously equatorward with many 2002 anomalies exceeding one standard deviation of the mean. At 27.8 km offshore in the jet in July, the anomaly ranges from 0.08–0.11 m s^{-1}. The anomalous equatorward flow in July averaged over deployments at 27.8, 46.3 and 83.3 km offshore are 0.08, 0.07 and 0.07 m s^{-1} for the 15, 30 and 45 d period, respectively.

4. Discussion and Conclusions

[13] By using a five-year surface drifter data set, equatorward velocities in the core of the upwelling jet of the northern California Current were found to be on average 0.05–0.06 m s^{-1} faster in spring and summer 2002 than the average computed over 1998–2002. At this speed, anomalous water displacements of over a degree of latitude can occur in 20–25 days. Given a source of cold, Subarctic water to the north, this anomalous southward displacement is thus a plausible explanation for the relatively cool halocline water observed off Oregon during the summer of 2002 [*Freeland et al.*, 2003].

[14] The 0.12 m s^{-1} anomalous equatorward velocity measured at a mid-shelf mooring located 18.5 km offshore of Newport, Oregon [*Kosro*, 2003], is twice the average anomaly found here using Lagrangian displacements from surface drifters. The discrepancy is because the drifters sample along a meandering pathway and because they average over a spatial trajectory that may not always be near the center of the equatorward upwelling jet. The equatorward upwelling jet core is more likely to be found over the midshelf off Newport than off southern Oregon and northern California where it is often separated from the coast [c.f., *Huyer et al.*, 1978, and *Barth et al.*, 2000]. Note, however, that the drifter-derived anomaly in the center of the jet at 27.8 km offshore ranges up to 0.13 m s^{-1}, comparable to the mooring estimates. Despite the expected difference in these Eulerian and Lagrangian estimates, they are in agreement on the existence of anomalous equatorward transport in the northern CC during the first half of 2002. Most importantly, the drifter observations extend the single mooring results to a larger spatial area, both cross-shelf and along the coast.

[15] The in situ drifter observations of anomalous equatorward transport during the first half of 2002 is consistent with anomalous southward and onshore flow into the northern CCS as measured by cross-track altimeter surface velocities [*Strub et al.*, 2003].

[16] In their study of large-scale atmosphere-ocean anomalies in the northeast Pacific during 2002, *Murphree et al.* [2003] ascribe increased equatorward transport in the northern CCS to a combination of events: large-scale wind stress anomalies in the northeast Pacific leading to anomalous transport of Subarctic waters into the North Pacific Current (NPC); increased eastward transport in the NPC; and anomalously strong coastal upwelling over much of the CCS. The in situ drifter observations of increased

equatorward transport reported here are consistent with the large-scale forcing events described by *Murphree et al.* [2003] and provide a quantitative estimate of their combined effect, an increase of near-surface equatorward flow of 0.05–0.06 m s^{-1} (4–5 km d^{-1}).

[17] The observed cold halocline water is accompanied by high nutrients [*Wheeler et al.*, 2003] which, when upwelled over the shelf, fuel an increase in the amount of primary productivity off the Pacific Northwest [*Wheeler et al.*, 2003; *Thomas et al.*, 2003]. Further, an anomalously high amount of primary productivity could result in an excess of organic material falling to the bottom over the Oregon continental shelf which through respiration may lead to hypoxic bottom water conditions as observed during summer 2002 [*Wheeler et al.*, 2003; B. Grantham, personal communication].

[18] The increased equatorward velocity off the Pacific Northwest during spring-summer 2002 documented here is an example of interannual variability. The implications for the ecosystem in this region - increased nutrient supply and primary productivity - are of similar importance to those arising from another common form of interannual variability, namely the increased poleward velocity and warmer temperatures observed in this same region during the fall and winter of El Niño years.

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