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Altimeter estimates of anomalous transports into the northern California Current during 2000–2002

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[1] Surface transports into the California Current are calculated from TOPEX/POSEIDON altimeter surface height slopes during the 9.5 year period from October 1992–May 2002. These quantify the anomalous onshore and southward displacements of the water column during the 2000–2002 period, which had been hypothesized by others based on anomalous water properties observed in mid-2002 off Oregon. Anomalous eastward transport into the boundary between 52°–54°N occurred first (mid-2000 to mid-2001) followed by eastward transport into the boundary between 50°–52°N in 2001. Equatorward transports during 2001 and 2002 resulted in approximately 800 km of anomalous southward displacements during the 1.5 years prior to the anomalous observations off Oregon. This sequence suggests that both onshore and southward displacement anomalies off British Columbia and the Pacific Northwest contributed to the subarctic characteristics of the water observed off Oregon. *INDEX TERMS:* 4516 Oceanography: Physical: Eastern boundary currents; 4215 Oceanography: General: Climate and interannual variability (3309); 4279 Oceanography: General: Upwelling and convergences; 4283 Oceanography: General: Water masses; 4512 Oceanography: Physical: Currents. **Citation:** Strub, P. T., and C. James, Altimeter estimates of anomalous transports into the northern California Current during 2000–2002, *Geophys. Res. Lett.*, *30*(15), 8025, doi:10.1029/2003GL017513, 2003.

1. Introduction

[2] Cold, fresh and nutrient-rich water property anomalies in the California Current have long been attributed to inflow of water from the subarctic gyre [*Wickett*, 1967; *Chelton et al.*, 1982]. This inflow has been hypothesized to come from eastward inflow from the North Pacific Current [*Chelton and Davis*, 1982] or from anomalous equatorward flow along the British Columbia coast [*Freeland et al.*, 2003]. Warm and salty anomalies are hypothesized to come from the south [*Pares-Sierra and O'Brien*, 1989]. Satellite altimeter measurements now make the direct tests of these hypotheses possible, as demonstrated by the analysis of anomalous transports in the NE Pacific during the 1997–1998 El Niño [*Strub and James*, 2002].

[3] During summer of 2002, sampling during the U.S. GLOBEC NE Pacific cruises off Oregon found unprecedented subsurface anomalies of fresh and cold conditions in the halocline (20–150 m depth) [*A. Huyer*, pers. comm.; *Freeland et al.*, 2003], accompanied by high nutrient and surface chlorophyll concentrations, along with low bottom oxygen concentrations [*Wheeler et al.*, 2003; *Thomas et al.*, 2003; *D. Fox and B. Grantham*, pers. comm.]. In this paper we use TOPEX/POSEIDON (T/P) altimeter data to examine the anomalous transports into the northern part of the California Current, during the periods preceding the observed water property anomalies. Although the geostrophic calculations from altimeter data represent only surface velocities, observations in the California Current reveal high correlations between surface velocities and deeper velocities in the upper 100–150 meters [*Chelton*, 1984; *Kosro*, 2003], thus advecting the halocline.

2. Data and Methods

[4] Sea Surface Height (SSH) data used in this study come primarily from the TOPEX/POSEIDON (T/P) altimeters, with additional data from four tide gauge stations along the U.S. west coast (filled circles in Figure 1). Geostrophic velocities are calculated from the SSH slope between pairs of measurement points (altimeter crossovers or tide gauges), using the standard geostrophic method. These are multiplied by the distance between the observation points to represent surface transport (per unit depth), or by the time to give surface displacements over three-month periods. The altimeter data come from the NASA/NOAA Pathfinder project and have standard corrections applied. The long-term (9.5 year) mean is removed from each altimeter grid point to eliminate large, fictitious velocities caused by slopes in the unknown marine geoid. This also removes slopes associated with the long-term mean transports, which can not be separated from the geoid. For the four transports where tide gauges are used, the mean from the same 9.5 year period is also removed and the data are filtered to reduce the effects of coastal trapped waves. Seasonal cycles are calculated by averaging all representations of each season in the 9.5 year time series. Winter is DJF, etc. These mean seasonal values are subtracted from each individual season in the time series to create non-seasonal anomalies of transport and displacement. The final transports, velocities and displacements represent averages over ~250 km (the crossover spacing), with time scales of three months.

3. Results

[5] Figure 1 presents the non-seasonal anomalies of surface transport for the NE Pacific for summer of 2001 through spring of 2002. Darkened arrows represent "significant" transports, greater than those expected from random errors in the altimeter velocities [*Strub et al.*, 1997]. When averaged over 250 km and three months, conservative estimates of these errors are less than the scale arrow in

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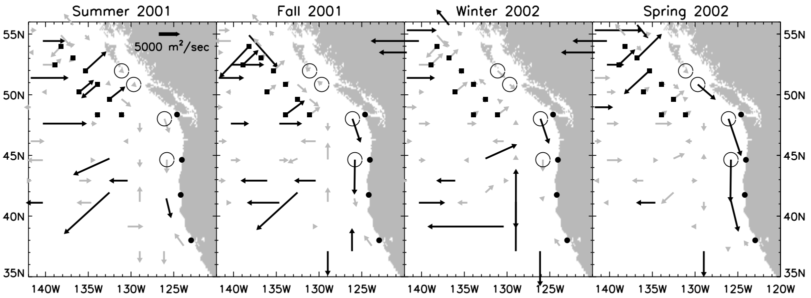

Figure 1. Non-seasonal anomalies of surface transport for summer (JJA) 2001 through spring (MAM) 2002. The long-term (9.5 year) mean and the mean seasonal cycle are subtracted to form the non-seasonal anomalies. Tide gauges are indicated by solid circles. The four alongshore transports averaged in Figure 2 are indicated by open circles; the onshore transports averaged in Figure 3 have solid squares at their bases.

Figure 1a (5000 m^2 s^{-1}, approximately 2 cm s^{-1} or 150 km of displacement in three-months). The transports of interest are the alongshore transports along the U.S. and Canadian coasts, as well as the "onshore" transports that carry water eastward into the boundary currents north of 48°N. Looking at the alongshore transports in the 200–400 km next to the coast, southward anomalies (corresponding to 100–200 km of displacement toward the equator in a season) appear from northern Washington to northern California from summer 2001 through spring 2002. These are strongest and most spatially extensive and coherent during spring 2002, extending to 55°N or beyond. A similar plot for summer 2000 through spring 2001 (not shown) reveals that these anomalous transports were continuously southward along the Pacific Northwest (PNW) from autumn 2000 through spring 2002.

[6] To better quantify the alongshore and onshore displacements, we form averages of the displacements of most interest. Figure 2 presents the mean three-month non-seasonal anomalies of alongshore displacements, averaging the four transports closest to the coast between 45°N–53°N (open circles in Figure 1). The unknown long-term mean that has been removed is expected to be of order 2–4 cm s^{-1}, corresponding to a 150–300 km displacement over three months. The seasonal cycle that has been removed is northward in winter and spring (445 km and 30 km per three-months, respectively) and southward in summer and autumn (300 km and 165 km per three-months, respectively).

[7] Considering the entire 9.5 year time series in Figure 2, there was little overall displacement during 1993–1996 (dotted line). Water simply fluctuated 450 km to the north and south over each annual cycle (not shown), after an initial displacement of approximately 200 km to the south. During the strong El Niño of 1997–1998, Figure 2 shows four consecutive three-month displacements of 150–350 km, resulting in a mean displacement anomaly of approximately 1000 km during the second half of 1997 and early 1998 (cumulative displacement jumped from −300 km to +700 km), with an additional increment of about 300 km in early 1999. By the end of 2000, the cumulative displacement from the beginning of the time series was approximately 800 km to the north of the origin. During the 12 months between December 2000 and November 2001, water was displaced approximately 400 km back toward the south, followed by another 350 km during the 6 months between December 2001 and May 2002.

[8] The actual motion is likely to be concentrated in a current that is much stronger and narrower than the 250 km width of the geostrophic calculations. Thus the displacements reported here represent an index of relative displacement strengths over the time series. The primary features evident are the large northward displacements over the course of a year during the El Niño and the nearly continuous southward transport anomalies for over two years starting around December 1999, strongest from September 2000 to May 2002. If water properties were truly conservative over periods of years, we might expect conditions to be abnormal from 1998 through 2001, returning to normal in 2002. In fact, water advected north during the El Niño takes on local characteristics over the winters of 1999–2000. The unique feature of this period is the length of the continuously equatorward anomalies, during which water with British Columbia characteristics is advected 800 km to the south, culminating in the exceptional anomaly in spring, 2002.

[9] East-West transport anomalies are quantified similarly, by calculating geostrophic velocities between crossovers and averaging those in the bands between 48°–50°N, 50°–52°N and 52°–54°N. Only the three onshore-offshore transports closest to the boundary (approximately 300–500 km from the coast) are averaged in each latitude band (vectors with solid squares in Figure 1). Figure 3 presents the non-seasonal three-month anomalies of displacement, roughly in the onshore direction. For these displacements, the seasonal cycles that are removed are very weak, with maximum

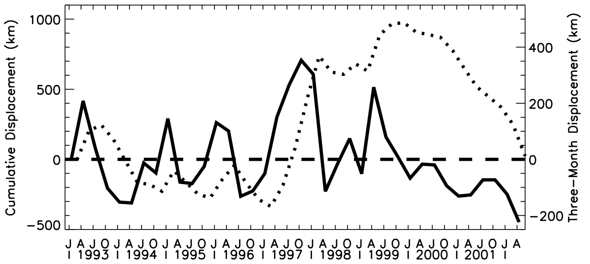

Figure 2. Non-seasonal anomalies of alongshore surface displacements (km), formed by averaging the four transports next to the coast between 45°–53°N in Figure 1: cumulative displacements (dotted line) and individual three-month values (solid line). Positive is northward.

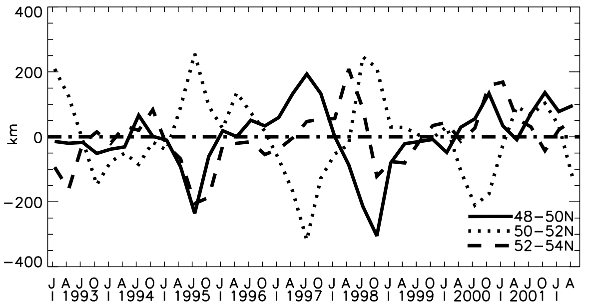

Figure 3. Non-seasonal anomalies of onshore surface displacements (km) in three latitudinal bands between 48°–54°N, formed by averaging the three onshore transports closest to the coast in each latitudinal band (solid squares in Figure 1). Positive is eastward.

displacements of approximately 35 km during a three-month season.

[10] One of the striking aspects of the time series is the out-of-phase relationship between onshore transports in the band between 48°–50°N (solid line) and those between 50°–52°N (dotted line). We interpret this as the result of the north-south movement of the terminus of the North Pacific Current (NPC) as it delivers water to the boundary. Onshore transports between 52°–54°N are north of the terminus but may indicate broadening and narrowing of the NPC. These transports indicate a poleward movement and narrowing of the NPC in 1995 (more transport between 50°–52°N, less between 48°–50°N and 52°–54°N) and again in 1998, with equatorward movement of the NPC in mid-1997 (prior to the appearance of El Niño effects), in 2000 and 2002. As a result of this out-of-phase relationship, the average onshore-offshore displacement between 48°–52° is usually less than 100 km over any three-month season and the net accumulated displacement is less than 150 km during 1993–1999 (not shown). It is significant that this out-of-phase relationship breaks down from mid-2001 to mid-2002, when there is a net accumulated displacement of 300 km toward the coast (not shown) between 48°–52°N. In fact, net displacements for all three latitiude bands during 2001 are eastward (approximately 200 km during the year averaging all three bands). This is the only year in the 9.5 year time series when the net onshore-offshore displacement is in the same sense in all three bands for a year at a time.

4. Discussion

[11] *Freeland et al.*, [2003] hypothesized that equatorward and/or onshore advection of subarctic water created the cold, fresh and rich anomalies found in the pycnocline off the PNW in summer of 2002. Large-scale transports calculated from altimeter SSH slopes presented above support both types of hypothesized transport anomalies and provide a larger-scale context within which this occurred. The altimeter data show that:

[12] ● Anomalous transports were southward in the 300 km next to the PNW coast from 2000–2002, strongest in 2001 and the first half of 2002; these created southward displacement anomalies of approximately 800 km, with the most rapid southward transport occuring during the first half of 2002.

[13] ● Accumulated anomalous onshore displacements of 300–400 km occurred first between 52°–54°N and 48°–50°N from mid-2000 to mid-2001, then between 50°–52°N from March 2001 to February 2002, then again between 48°–50°N from June 2001 to May 2002.

[14] The significance of the onshore displacements lies in the depletion of macronutrients along the boundaries of British Columbia and the PNW in summer and the increase in those nutrients in the offshore waters north of approximately 50°N. *Anderson et al.* [1969] compiled data available at the time to show that nitrate minima (late summer values) in the 5° next to the coast between 45°N–60°N are close to zero, while the minima recorded in the next 5° offshore do not drop below 6.5 μM north of 50°N. *Whitney and Freeland*, [1999] compiled more recent data to show that the region of summer depletion along line P (approximately 50°N) has expanded to cover approximately 600 km next to the coast in the 1990s. The offshore gradients in nitrate concentrations are approximately constant from 600 km to 1500 km offshore (Station P), with magnitudes estimated to be 0.6 ± 0.3 μM per 100 km [*Whitney and Freeland*, 1999]. Examination of drifter movements in the eastern North Pacific Current show that onshore displacements into the boundary currents from over 500 km offshore take 3–6 months. Thus, the region depleted in summer is replaced over the course of the normal season and additional displacements of 300–400 km to the east would elevate nitrate levels by several μM. In the alongshore direction, *Wheeler et al.* [2003] estimate gradients of 4 μM per degree of latitude (100 km) along the PNW, increasing to the north. *Wheeler et al.* [2003] find nitrate levels in summer 2002 to be 10 μM greater than during other years. The anomalous displacements of several hundred kilometers onshore and 800 kilometers to the south during 2001 and the first half of 2002 are thus more than sufficient to account for an increase of 10 μM in mid-2002.

[15] The magnitudes of the southward transports (800 km to the south during 2001 and the first half of 2002) are also in approximate agreement with estimates by *Freeland et al.* [2003], who find an additional displacement of 500 km needed to bring the observed water properties from the north. *Freeland et al.* [2003] also observed anomalous conditions as early as July 2001 (their Figure 5), implying that the advection of the anomaly began before mid-2001 and progressed from north-to-south over the course of a year. This is consistent with the continuous southward anomalies seen in the altimeter transports from December 2000 to May 2002.

[16] *Bograd and Lynn*, [2003] find a similar (fresh, cold, nutrient-rich) subsurface anomaly in the core of the California Current (150–350 km offshore) off southern California (33°–35°N) in summer 2002. If the anomaly reported by *Freeland et al.* [2003] at 50°N in mid-2001 moved 1500 km south in one year, it would account for the *Bograd and Lynn* observations. The velocities needed for this movement are only approximately 300–400 km per 3-month season (4–5 cm s^{-1}), values similar to the climatological values found by *Chelton* [1984]. Thus the observations of *Bograd and Lynn*, [2003] are consistent with the continuous southward movement at "normal" climatological speeds of cold, fresh and nutrient rich anomalies, introduced into the northern region of the system by mid-2001.

[17] *Kosro*, [2003] presents alongshore displacements derived from measured currents at a mooring on the shelf off central Oregon between May 1998 and August 2002. Displacement anomalies show an increase in northward displacements in early 1999 (similar to the altimeter record in Figure 2) and again in mid-2000. Beginning in January 2001, these measured shelf velocities show a nearly continuous displacements toward the south, with a net surface displacement of over 1500 km from January 2001 to May 2002. Between January 2002 and June 2002, mean displacements were 1100 km at the surface and 600 km at 64 m depth. Although the magnitudes of the measured currents over the shelf are 2–3 times those estimated from the altimeter, the general agreement of the sense of the two time series is remarkable, given the difference in scale between the 250 km wide altimeter transports and the point measurement over the shelf.

[18] A final comparison can be made to the results of *Murphree et al.* [2003], who used the wind-driven OSCURS model to calculate trajectories of water parcels for the first 9 months in each of eight years (1995–2002). The trajectories all start at 136°W, 47.5°N and move eastward in the NPC. During five of the eight years they then move northward into the Alaska Current. Only during 2002, 2000 and 1996 did the trajectories move into the California Current, reaching their southernmost position in 2002. *Murphree et al.* [2003] interpret the trajectories as showing southward displacement of the bifurcation of the NPC in 1996, 2000, and 2002. Our interpretation of the changes in onshore altimeter transports (Figure 3) is that the bifurcation point was shifted southward during 1997, 2000, and 2002, in agreement with two of the three *Murphree et al.* [2003] years. The degree of agreement is fairly good, given that our calculations make no use of the wind-driven Ekman flow, while the OSCUR model includes only wind forcing and a constant geostrophic surface velocity climatology (no year-to-year differences in geostrophic currents).

5. Conclusions

[19] Considering the entire 9.5 year record of onshore and alongshore surface transports, as calculated by the altimeter alone, the period from mid-2000 to mid-2002 is different from the rest of the record in two ways in the northern California Current: (1) A sustained period of southward transport anomalies produced displacements of 800 km between 45°–53N° (bringing water from the British Columbia coast to central Oregon); and (2) Net onshore displacements were to the east between 48°–54°N during 2001. This is the only year in the record for which net transport between 48°–54°N is eastward. The timing is such that offshore water was brought to the boundary first in the northern extreme (52°–54°N), then progressively farther south, as the southward transport anomalies strengthened. The general gradients of nutrients (increasing to the north and offshore) would have caused a convergence of the enriched water along the Pacific Northwest.

[20] **Acknowledgments.** This paper was motivated by Jane Huyer's original insight into the significance of the extreme anomalies observed in the GLOBEC cruises during summer 2002 and her energy in inspiring her colleagues to probe other aspects of the phenomenon. Pat Wheeler helped explain the connections to offshore nutrients. The work was supported by the U.S. GLOBEC NEP project with funding from NSF/NASA grant OCE-0000900 and the Jason-1 project with funding from NASA/JPL grant 1206714. This is Contribution Number 391 of the U.S. GLOBEC program, jointly funded by the National Science Foundation and the National Oceanic and Atmospheric Administration.

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