Drifter Behavior on the Oregon–Washington Shelf during Downwelling-Favorable Winds[*]

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ABSTRACT

Drifters released offshore of Oregon during predominantly downwelling favorable alongshore winds during three different deployments (October 1994, January 1998, and September 1998) display similar behavior: after being advected around in the offshore eddy field, they move onshore to a particular isobath and are advected poleward alongshore, without coming ashore. Numerical modeling results suggest that this may be due to downwelling circulation creating a marginally stable density gradient on the shelf inshore of the downwelling front, thereby increasing the vertical eddy diffusivity, which reduces the effective cross-shelf Ekman transport to nearly zero. The downwelling front itself is accompanied by a poleward jet, which carries drifters rapidly to the north. This behavior is consistent with previous modeling results.

1. Introduction

Drifter data from the Oregon–Washington continental margin during the fall–winter season, during which the winds are predominantly downwelling favorable (poleward), show that drifters can be advected hundreds of kilometers poleward. Drifters move onshore during downwelling winds but stop their cross-shelf progress some distance from the coast and move poleward. A significant number of the drifters are not advected all the way to the coast by the presumed onshore surface Ekman transport. Instead the drifters move poleward over long distances while maintaining a roughly fixed distance from the coast. These drifters maintain their separation from the coast even during intense downwelling-favorable winds.

This behavior appears to be consistent with the modeled results of Allen and Newberger (1996) and Austin and Lentz (2002), where downwelling favorable winds produce an ''inner shelf'' region inshore of the downwelling front. This region is characterized by a lack of vertical stratification, and strong mixing there produces large Ekman number flows. The primary alongshore momentum balance in these regions is between surface and bottom stress, with very little stress being diverged to drive surface or bottom Ekman layers. Hence, cross-shelf circulation in this region is extremely weak, and the circulation resembles Couette flow (e.g., Kundu 1990, p. 268). In this paper we hypothesize that this change in flow regime (from the surface Ekman transport regime offshore of the downwelling front to the well-mixed region inshore of the downwelling front) may be responsible for the behavior of the surface drifters. Namely, offshore of the front the drifters are advected poleward and onshore in the surface Ekman layer, and onshore of the front they are simply advected poleward (Fig. 1). The offshore displacement of the drifter as it moves northward inside the front is a function of the offshore distance at which the drifter crosses over the downwelling front.

Long poleward trajectories of surface drifters have been noted in a few other systems. Off central California. Winant et al. (1999) observed that near-surface-drogued drifters made significant northward displacements during periods of relaxation after upwelling winds. Royer et al. (1979) observed several relatively deeply drogued (35 m) drifters travel westward along the Alaska coast in several deployments during the spring and summer of 1976, during which winds were weakly downwelling favorable (i.e., to the west). These drifters approximately followed the dynamic topography. However, none of the drifters from these two deployments were observed during periods of strong downwelling favorable winds, which is the case we will discuss here.

Obviously, the relatively small number of drifters reported here and the complexity of the system prevents

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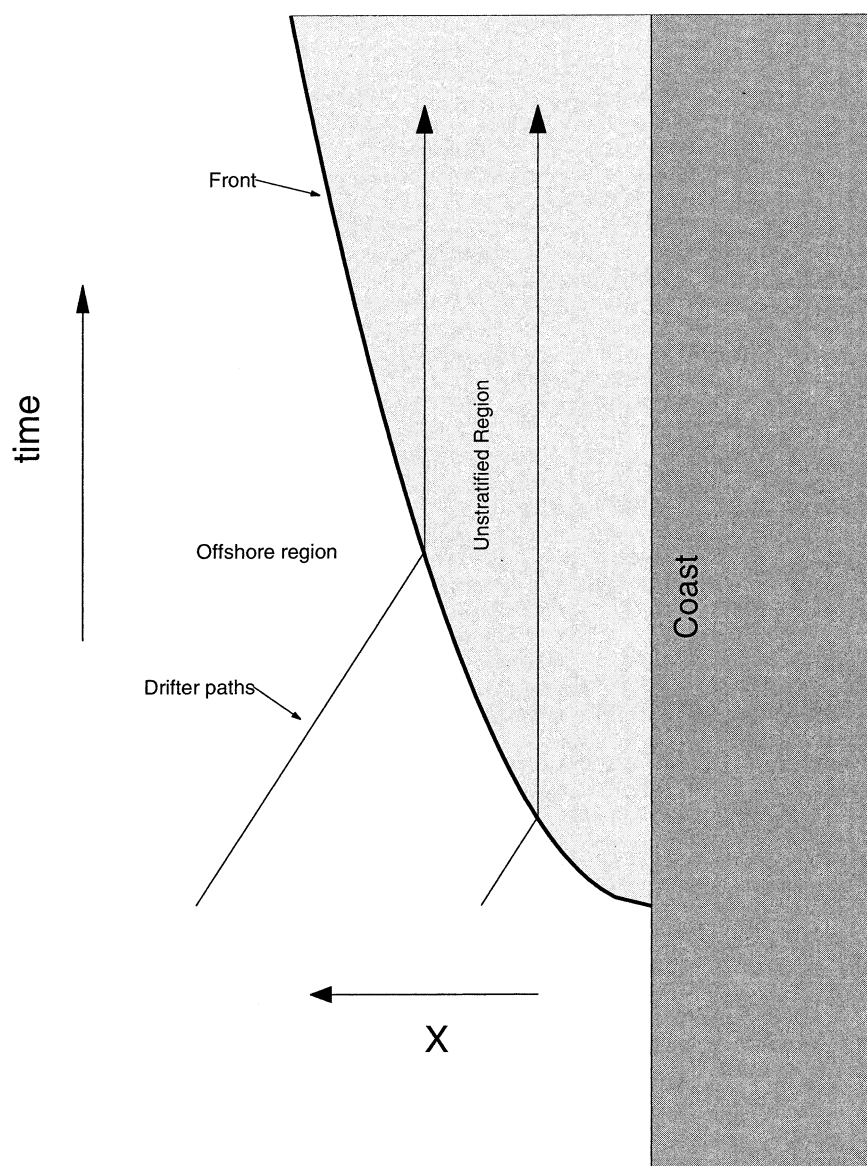E-mail: jay@ccpo.odu.edu

FIG. 1. Simple cartoon of trapping region.

2. Drifter observations

us from stating conclusively that this is indeed the sole cause of the drifter behavior. Since the spatial and temporal coverage of the drifter paths is not sufficient to yield a statistical description of the flow field, the drifter tracks are treated in a qualitative sense only. We intend for this paper to present new data and to suggest a simple dynamical explanation consistent with that data. We will consider the observational evidence (section 2) and present results from a two-dimensional model similar to that used by Austin and Lentz (2002) to support the hypothesis outlined above (section 3).

2. Drifter observations

As part of the Coastal Jet Separation Experiment (Barth and Smith 1998; Barth et al. 2000) surface drift-ers were released in August 1994 over the shelf near Coos Bay, Oregon (43.22°N). During the Global Eco-systems Dynamics Northeast Pacific (GLOBEC NEP) Program, surface drifters were released at regular in-tervals off Newport, Oregon (44.65°N). Data from the GLOBEC drifters are presented for releases in January 1998 and September 1999. 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 seven times per day. The position data is then low-pass filtered [using the pl64 low-pass filter (Beardsley et al. 1985)] to remove inertial motions, leav-ing the subinertial motion of the drifter. Since the focus of this work is on the dynamics of the drifters near the coast, the behavior of the drifters north of 51°N will be

ignored beyond where the drifters enter the Alaskan archipelago. The alongshelf low-pass filtered wind stress time series from a NDBC C-MAN (National Data Buoy Center Coastal-Marine Automated Network) station CARO3, at Cape Arago, Oregon (43.25°N) will be presented with the drifter paths. CARO3 was used because most of the NOAA NDBC buoys and C-MAN stations along this portion of coast were not functioning during February 1998. The time series of alongshelf wind stress from this station does not differ significantly from that observed at DESW1 (Destruction Island, Washington, 47.68°N), close to the northern extent of the region covered by the drifters. Alongshore wind stress events observed at DESW1 are roughly equal in strength to that observed at CARO3, though they occasionally lead CARO3 by 1–2 days. This suggests that the forcing observed at CARO3 is representative of the alongshore wind stress over the region of interest.

a. August 1994 release

Two drifters were released on 24 August 1994: drifter 22251 at 43.35°N, 124.68°W and drifter 22252 at 43.345°N, 124.72°W, approximately 4 km apart (Fig. 2). Both drifters are initially advected offshore in the separating coastal upwelling jet (Barth and Smith 1998). One (22252) executes a revolution around an offshore cyclone continuous with the coastal upwelling jet before being caught in a second offshore cyclone (along 128°W) for 3 months. The other drifter (22251) meanders in the weak offshore eddy field. At different times during the winter (late November 1994 for 22251, late December 1994 for 22252), the drifters are advected rapidly onshore onto the shelf, both during downwelling-favorable wind events. Neither drifter makes it all the way to the coast, both being trapped inshore of the 200-m isobath, though they do occasionally meander over the 200-m isobath during their transit (the shelf break is approximately at the 200-m isobath). The drifters proceed poleward along the coast at approximately 0.1 m s^{-1}, with maximum alongshelf speeds of approximately 0.4 m s^{-1}. As they are advected alongshelf northward, they maintain their distance from the shore for approximately 700 km, from the Oregon shelf to the northern tip of Vancouver Island, at which point drifter 22251 enters the Alaskan Archipelago (around the beginning of January 1995). Drifter 22252 comes ashore on northern Vancouver Island on approximately 13 May 1995. An estimate of the cumulative cross-shelf Ekman displacement due to the alongshore wind (section 3c and Fig. 12, dashed line) is much larger than the observed cross-shelf displacement of the drifters. This is true in all three of the deployments discussed here.

b. January 1998 release

As part of the GLOBEC NEP program, eight drifters were released along the Newport hydrographic line (44.65°N) between 30 January and 2 February 1998, during the downwelling season. Drifters were released spanning the shelf out to 155 km offshore with separations ranging from 9 to 37 km, but typically 18.5 km (Figs. 3a,b). The drifter paths are broken up into two panels (same scale) for increased legibility.

A conductivity–temperature–depth (CTD) section of potential density taken at the time of the drifter deployments (Fig. 4a) shows isopycnals intersecting the bottom largely offshore of the 150-m isobath. A small wedge of lighter water is observed on the inner shelf, due largely to freshwater runoff.

The outermost four drifters all moved rapidly onshore (roughly 0.3 m s^{-1} eastward) on or around 12 February near 46°N (Fig. 3a), while all of the drifters are advected northward during the entire deployment. The next inshore drifter (30560) is initially advected to the north, but then begins to meander near 46°N before ultimately coming ashore on 5 April 1998. The two drifters over the shelf break (200-m isobath; 30562 and 30565) are advected rapidly to the north at an average speed of 0.26 m s^{-1} and up to a maximum of 0.63 m s^{-1} in a poleward jet over the inner continental slope. This jet is anomalously strong due to the 1997–98 El Niño (Kosro 2002), similar to an increased northward transport documented during the 1982–83 El Niño by Huyer and Smith (1985). The outermost four eventually join up with the two shelf-break drifters after the former move onshore near 46°N. The innermost drifter is advected very rapidly northward (up to 0.7 m s^{-1}) during the entire deployment, until it goes aground on Vancouver Island around 10 February 1998.

c. September 1998 release

This set of drifters was released on 24–25 September 1998 across the shelf at Newport before the wind was predominantly downwelling favorable (Fig. 5c). A density section at 44.65°N (Fig. 6a) shows density contours spanning the shelf. By 16 November (Fig. 6b), the isopycnals have been displaced downward by a series of small downwelling-favorable wind events (Fig. 5c), intersecting the bottom at around the 50-m isobath.

Both drifters 22248 and 22243 make their most significant onshore progress during mid- to late November, during the first of a series of strong downwelling-favorable wind events. After transiting 380 km poleward (thick cyan curve; Fig. 5b), drifter 22248 ran aground during a moderate downwelling wind stress event on 12 December. Drifter 22243 remained over the shelf near Newport (44.6°N) for six weeks before moving consistently poleward starting 6 November (thick green curve; Fig. 5a). The midshelf (60–80 m) location of the downwelling jet carrying drifter 22243 at the beginning of its poleward transit (6 November) and the location of the downwelling front sampled on 15 November (Fig. 6b) are roughly coincident. During its northward transit over the inner shelf, strong alongshelf advective events
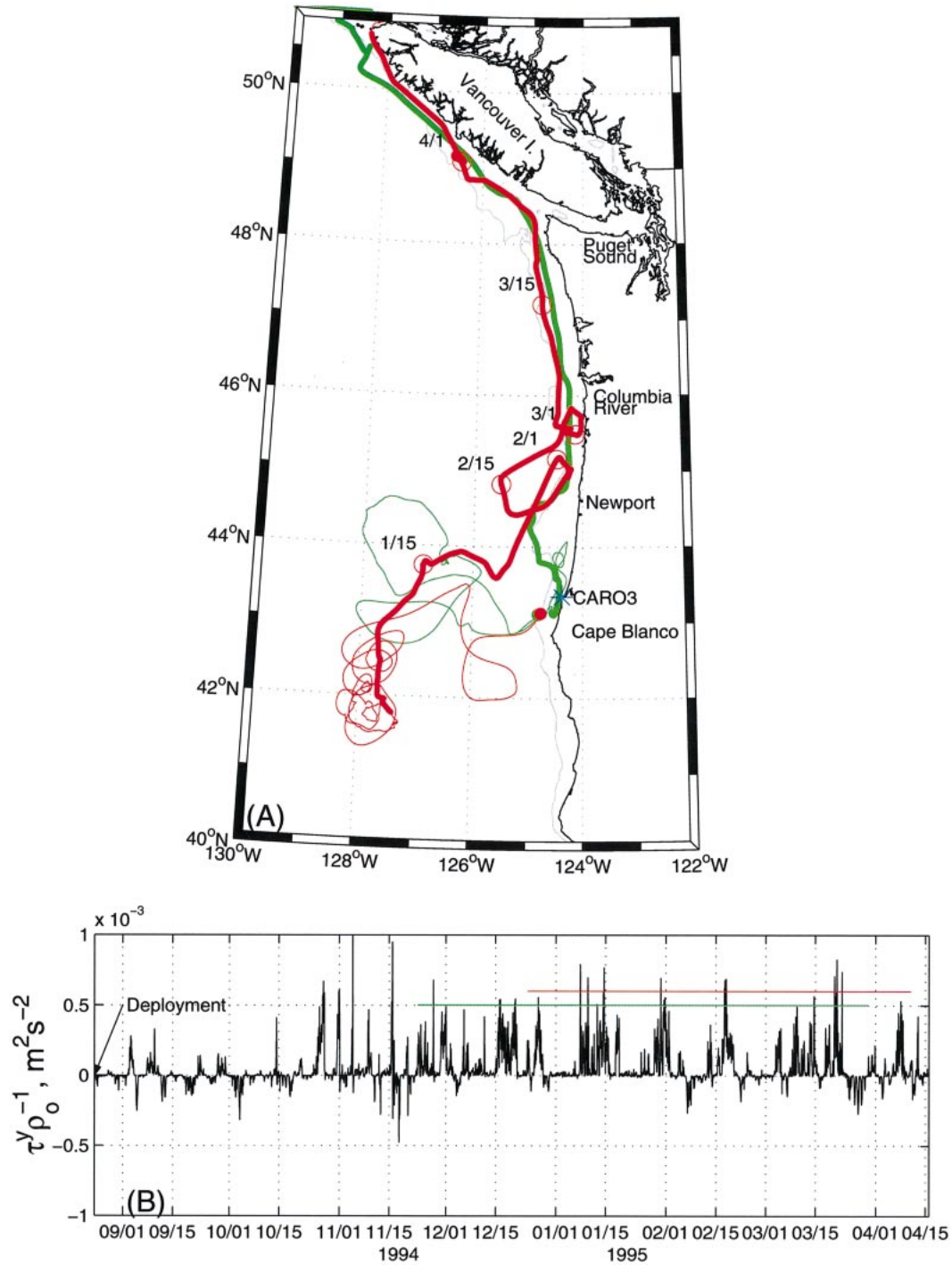
FIG. 2. (a) The paths of two drifters released on 24 Aug 1994 within 4 km of each other (green: 22251, red: 22252). The position of the CARO3 NDBC meteorological station is marked with a star. The filled colored dots represent the deployment positions. The open red circles are representative positions with dates of drifter 22252. The thickened lines correspond to the time periods shown in (b), and represent the portion of the time series when the drifters are moving rapidly onshore or poleward. The light gray line is the 200-m isobath. (b) The alongshelf wind stress at station CARO3. Positive is downwelling favorable. Red and green lines correspond to time periods of rapid onshore or poleward movement of the drifters.
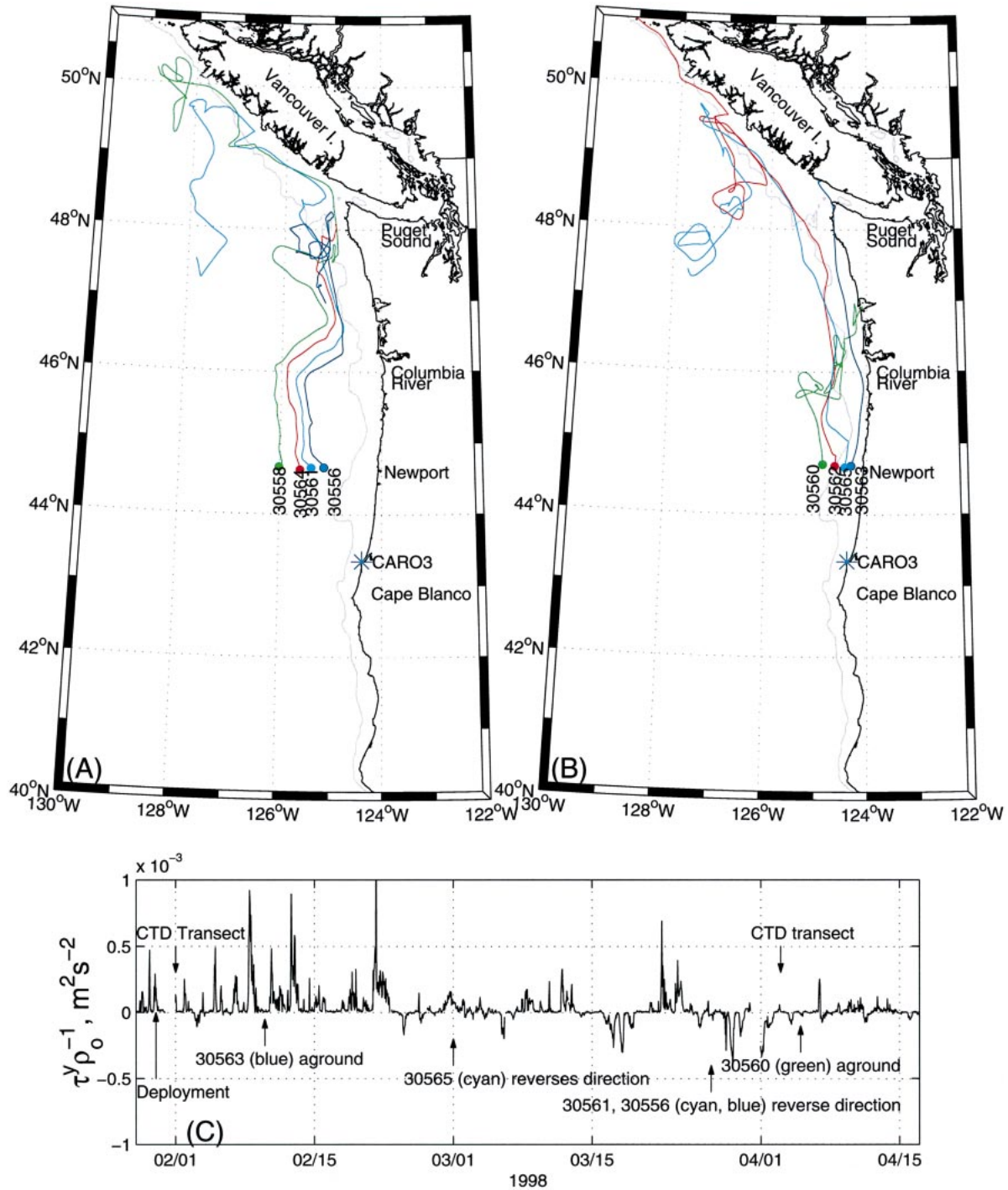
FIG. 3. As in Fig. 2 but for the Jan 1998 deployment. The two map panels represent four drifters each of the same deployment, and are separated only to improve legibility. Drifter paths from 31 Jan to 15 Apr are shown. In order of decreasing deployment distance from shore: (a) 30558 (green), 30564 (red), 30561 (cyan), and 30556 (blue), (b) 30560 (green), 30562 (red), 30565 (cyan), and 30563 (blue). (c) Timing of the CTD transects shown in Fig. 4.

corresponded to large alongshelf wind stress events on 15 and 25 November and 7 December. Drifter 22247 moved onshore then poleward in response to down-welling-favorable winds beginning around 8 October

before grounding on 15 October. Drifter 23682 moved offshore and equatorward before turning poleward and onshore in early December. It reached as far north as 44.62°N over the shelf before being advected southward
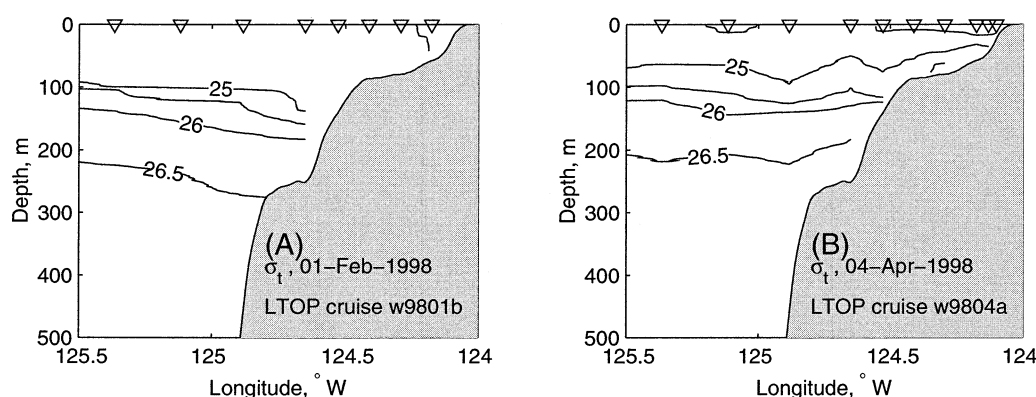
FIG. 4. Density sections at 44.65°N taken on (a) 1–2 Feb 1998, soon after the deployment of the eight drifters shown in Fig. 3 and (b) on 3 Apr 1998.

for six weeks. In early February, it again transited poleward over the shelf for 316 km before grounding north of Newport on 19 February 1999. Last, drifter 23681 moved onshore starting in February 1999 and then transited 430 km poleward over the shelf before grounding on 16 March 1999.

In summary, all five drifters released in September 1998 eventually returned to the shelf and transited poleward.

A bottom-mounted ADCP recorded data over the period May 1998–December 1999, a period of roughly 19 months (P. M. Kosro, Oregon State University, 2001, personal communication). The ADCP was located roughly 16 km offshore of Newport along the Newport hydrographic line (44.65°) in 80 m of water. The major axis (i.e., principal axis of variation) of the velocity at 12 m (the shallowest uncorrupted data available) was oriented at roughly 28°T, just onshore of being oriented fully alongshore poleward. The orientation of the major axis did not show any significant variation as a function of season. The magnitude of the major axis, however, varied from 0.104 m s^{-1} in May–August to 0.209 m s^{-1} in November–February, due largely to the increased magnitude of wind events between these two periods. This is roughly consistent with the change in magnitude of the major axis of the wind stress, which is oriented alongshore. The magnitude of the major axis of the wind stress increased from 0.5×10^{-1} to 1.4×10^{-1} N m^{-2} between the summer months (May–August) and the winter months (November–February), respectively. However, the minor axis of the 12-m current, oriented cross-shelf did not vary between these two seasons, with a magnitude of 0.048 m s^{-1} in November–February and 0.046 m s^{-1} in May–August. This suggests that during the winter months, when the ADCP was inshore of the downwelling front, the cross-shelf response to the alongshore wind is considerably weaker in the winter than it is in the summer. This is consistent with the hypothesis posed here, in that the cross-shelf response is significantly weaker when stratification is removed.

d. Northward drifter statistics

To complete the description of the drifter data, statistics based on all the poleward trajectories for drifters released in 1998–99 are presented. A total of 21 drifters released from January 1998 to September 1999 transited onshore and poleward near the continental shelf (Fig. 7). Some drifters provided more than one northward trajectory if their poleward transit was interrupted by periods of equatorward motion. The average northward drifter displacement over the shelf was 421 km (standard deviation 240 km), with a minimum distance of 57 km and a maximum of 1030 km (Fig. 8). The drifters spent an average of 25.3 ± 14.9 days during their poleward trajectories and averaged a northward speed of 0.24 ± 0.08 m s^{-1} (Fig. 8). The maximum poleward velocity achieved by an individual drifter was approximately 1 m s^{-1}. These statistics back up the conclusions reached from considering individual releases over the shelf; drifters tend to be advected long distances alongshelf before grounding. Last, we note that the 15-m velocities near the coast north of 45°N derived from drifter data reported by Miller et al. (1999) are strongly influenced by the drifters released at Newport (44.6°N) as part of our projects. Since drifter data north of the release location can only be obtained in the presence of poleward currents as described here, the mean velocities reported by Miller et al. (1999) are biased northward.

3. Numerical models of downwelling: Drifter behavior

a. Model configuration

A 150-day period starting on 19 October 1994 was studied using a highly simplified two-dimensional model. The purpose of the model is not to attempt a simulation of a particular drifter trajectory; rather, it is to observe the behavior of a modeled drifter under semi-realistic conditions. Stratification typical of late fall conditions was used to initialize the runs (Fig. 9a). An averaged bathymetry profile was taken from the
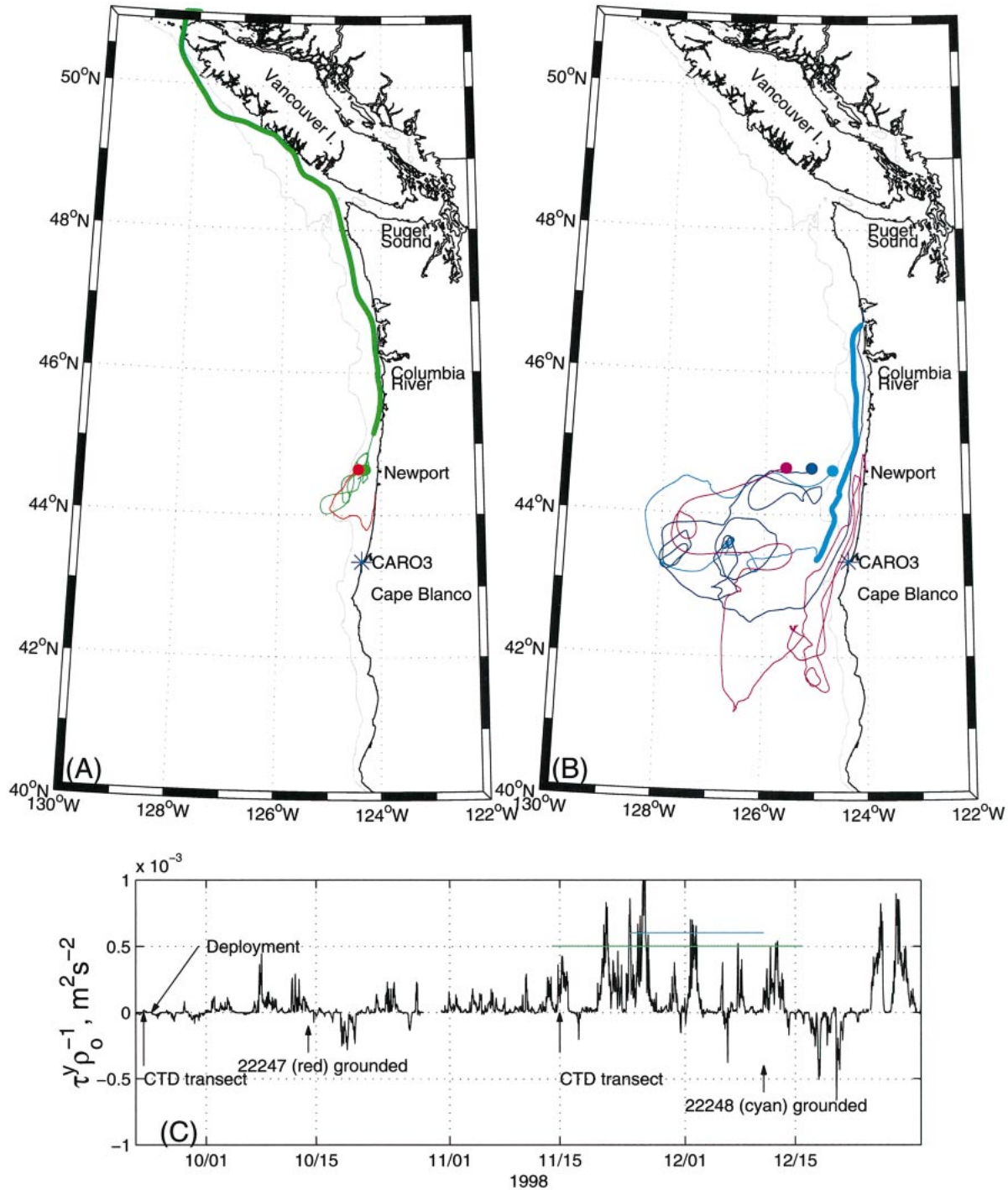
FIG. 5. As in Fig. 2 but for the Sep 1998 deployment: 22243 (green), 22247 (red), 22248 (cyan), 23681 (blue), and 23682 (magenta).

Oregon–Washington shelf (Fig. 9b). A deep interior 300 km wide (3000 m) was appended to the model domain to avoid issues associated with the finite nature of the domain. Alongshore winds measured at the CARO3 C-MAN station were used to estimate stress using the algorithm of Fairall et al. (1996), which was used for surface forcing. The decorrelation length scale in this region is greater than 1000 km (Halliwell and Allen 1984), justifying the use of stress estimates from a single location. The Princeton Ocean Model (POM: Blumberg and Mellor 1987) is used for the simulation, with the Mellor–Yamada 2.5 turbulence submodel (Mellor and Yamada 1982) providing the mixing parameterization. The numerical model configuration is the same at that
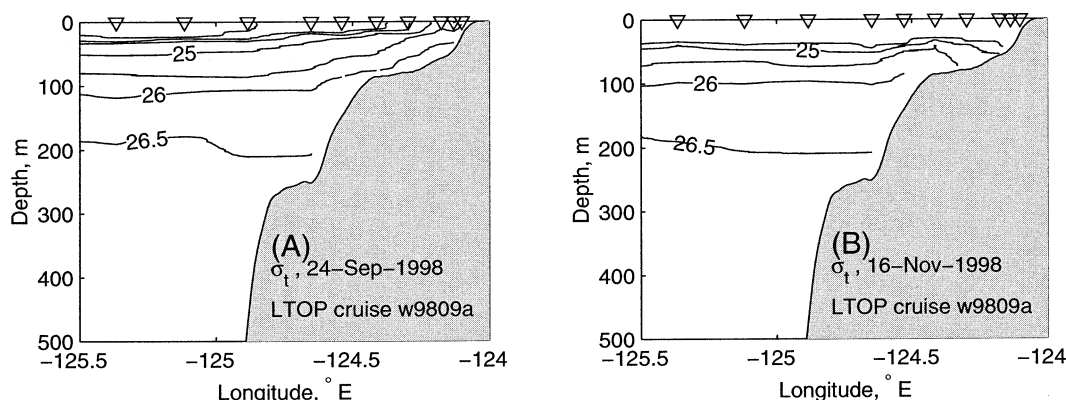
FIG. 6. Density sections at 44.65°N taken on (a) 24 Sep 1998, soon after the deployment of the four drifters shown in Fig. 5, and (b) on 16 Nov 1998.

described in Austin and Lentz (2002). The model utilized an internal (external) time step of 300 (15) s and 40 sigma levels, with increased vertical resolution near the surface. The horizontal resolution was proportional to the water depth, with a resolution of 200 m near the coast, increasing to over 4200 m in the central portion of the domain. Near the shelf break, the interior vertical resolution is roughly 6 m and decreases as the water depth decreases toward the shore. Runs described here differ from those presented in Austin and Lentz (2002) through the use of realistic bathymetry, forcing, and initial stratification.

b. Model results

Model results at day 68 (Fig. 10), during a moderate downwelling wind event, show that the pycnocline has been displaced roughly 40 km offshore to about the 180-m isobath. Streamlines show some onshore flow at the surface offshore of this front, balanced by offshore motion in the bottom layer, but weak or no circulation onshore of the downwelling front. This sense of circulation is consistent with the steady displacement of the downwelling front over the course of the season. The weak circulation inshore of the front is due to a weak cross-shelf density gradient that, in the presence of downwelling circulation, leads to a marginally unstable vertical density gradient, which in turn leads to large eddy diffusivities and hence weak cross-shelf circulation (Austin and Lentz 2002). Some evidence of symmetric instabilities appears present around the shelf break (Allen and Newberger 1998). The near-surface alongshore currents are intensified in the vicinity of the front (on the order of 0.80 m s^{-1}), and are poleward throughout the entire shelf. Though weaker on the inner shelf, near-surface velocities are still considerable, in this particular realization roughly 0.30 m s^{-1}. These values are consistent with the alongshore velocities observed with the drifters.

The density along the bottom as a function of time and offshore distance (Fig. 11) shows the progression

offshore of the downwelling front through the season. The superimposed heavy line represents the scaled estimate of offshore displacement of a downwelling front in a two-dimensional model derived by Austin and Lentz (2002):

$$X_f(t) = \sqrt{\frac{2 \int_0^t \tau(t')\, dt'}{\rho_0 \alpha f}}, \qquad (1)$$

where X_f is the predicted frontal position, τ is the alongshore wind stress, f is the Coriolis parameter (10^{-4} s^{-1} here), and α is the bottom slope (0.005 here, as the front stays on the shelf). This scaling suggests that the front is displaced steadily farther offshore throughout the downwelling season. The scaling does not take into account the poorly understood relaxation behavior that Austin and Barth (2002) discuss for the upwelling case. However, it can be expected that the frontal displacement does increase throughout the season. Therefore, drifters caught on the inner shelf early in the season are likely to be trapped closer to shore than those trapped later in the season.

c. Simulated drifter behavior

To determine whether, at least qualitatively, the circulation structure described here could account for the behavior of the surface drifters described in section 2, simulated "drifters" were advected using data from the model. This model does not include any of the physics that would cause the mesoscale eddy field presumably responsible for the initial behavior of the drifters in the field; the numerical model only simulates the downwelling circulation behavior. Drifter trajectories were calculated from the model output by taking the surface velocity fields and integrating forward in time, given an initial location $\mathbf{X}(0)$:

$$\mathbf{X}(t) = \mathbf{X}(0) + \int_0^t \mathbf{U}[\mathbf{X}(t')]\, dt'. \qquad (2)$$
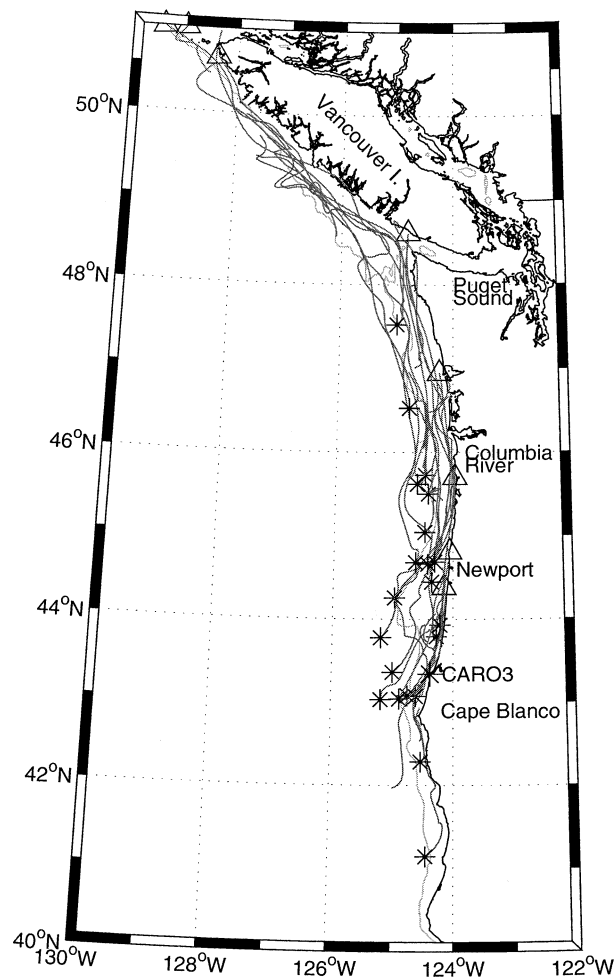
FIG. 7. Poleward trajectories of drifters released off Newport, OR, from Jan 1998 to Sep 1999. Stars indicate locations where drifters started their onshore and poleward motion, while triangles indicate where drifters came ashore. The three triangles at 51°N indicate where active drifters entered the Alaskan archipelago. The 200-m isobath is shown in gray.

FIG. 8. Statistics for the poleward trajectories of 21 drifters released from Jan 1998 to Sep 1999. Distances, times, and speeds (means ± one standard deviation) for the trajectories are computed for the total poleward motion of each individual drifter.

The velocity at a given arbitrary point **X** is determined by linearly interpolating the velocity field at the appropriate time from the model grid at hourly intervals. This yields a time series of drifter position (Fig. 12). A drifter released 200 km offshore is shown as a dashed curve, along with the frontal position prediction X_f. The downwelling front passes under the drifter at approximately day 60, significantly changing the trajectory of the drifter. Two significant cross-shelf excursions occur as the drifter crosses through the frontal jet itself. Once on the inner shelf, the drifter still makes small cross-shelf movements during downwelling events, but these excursions tend to be weak and also tend to be followed by a small offshore displacement during the following geostrophic adjustment (Austin and Lentz 2002). The weak cross-shelf flow field advects the drifter across the shelf but does not change the position of the isopycnals. This is due to the fact that the density field is subject
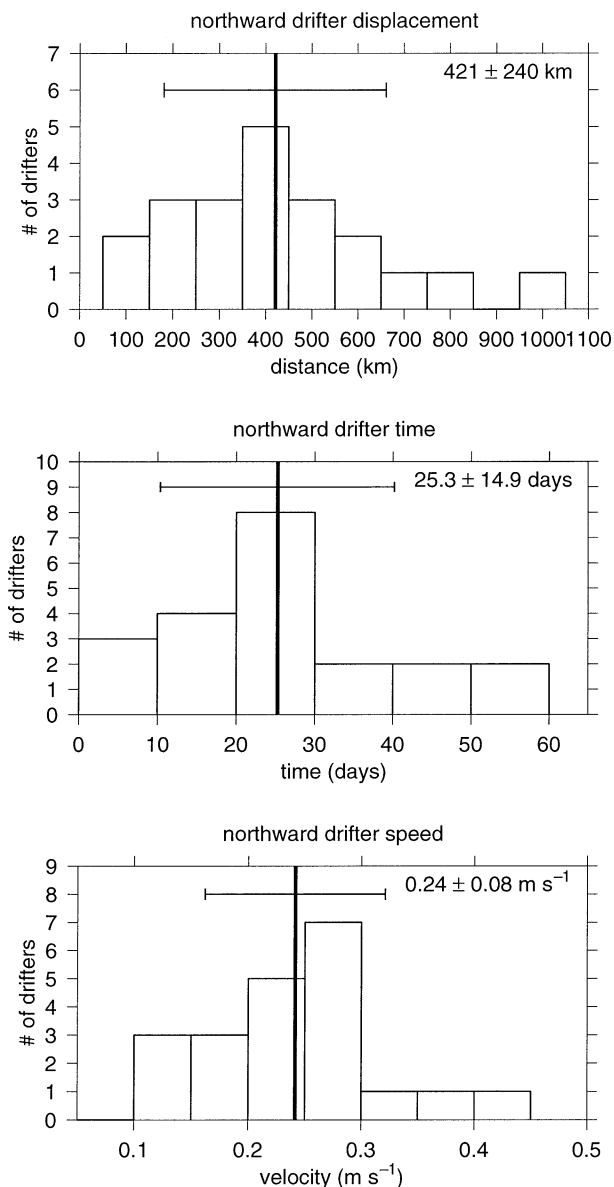
to mixing as well as advection, and the drifter only responds to advection.

A comparison of the cross-shelf position of the drifter and a simple scaling of the cross-shelf displacement due to a spatially invariant Ekman transport estimate is also informative. In Fig. 12, the cross-shelf position of the model drifter is plotted along with a simple scaling of cross-shelf displacement due to Ekman transport:

$$X_{Ek}(t) = X_0 + \frac{1}{h_{Ek}} \int_0^t \frac{\tau^s(t')}{\rho_0 f} \, dt', \quad (3)$$
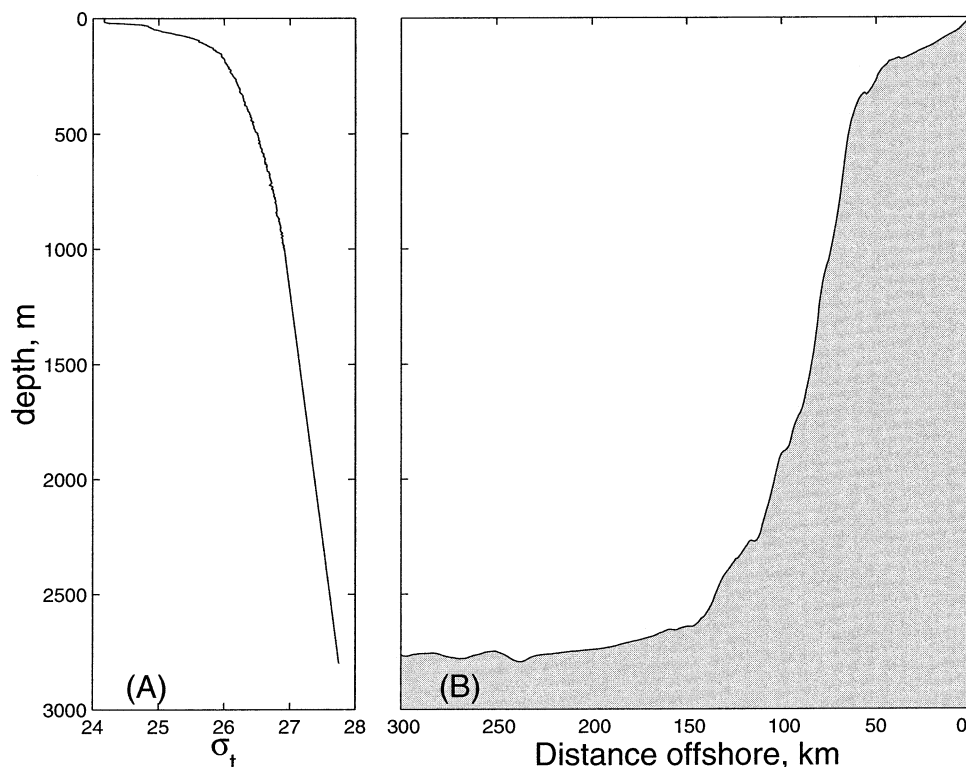
where h_{Ek} is some estimate of the depth of the surface

FIG. 9. (a) Initial vertical stratification used in model. (b) Bathymetry used for model.

Ekman layer. In this case, $h_{Ek} = 22$ m was chosen simply for its good agreement with the drifter behavior before day 60. However, after day 60, the simple Ekman model dramatically overestimates the cross-shelf progress of the drifter since this simple model does not take into account the role of the inner shelf.

4. Discussion

a. The role of freshwater runoff

Freshwater runoff is an important component of the nearshore circulation (e.g., Huyer and Smith 1978; Hickey 1998; Hill 1998) and may play a part in deter-

mining drifter behavior. Freshwater flow may drive an alongshore poleward buoyancy-driven flow that would act to augment the wind-driven flow modeled here. Further, freshwater runoff will intensify the cross-shelf density gradient that is naturally formed during downwelling winds. This increase in the cross-shelf gradient will lead to even stronger convective overturning as the front is steepened, further increasing the eddy viscosity and hence reducing the cross-shelf circulation (Austin and Lentz 2002). Model runs made with a freshwater source (not shown here) confirm this result, as drifters released into these models display the same basic behavior and the downwelling frontal position is not significantly im-
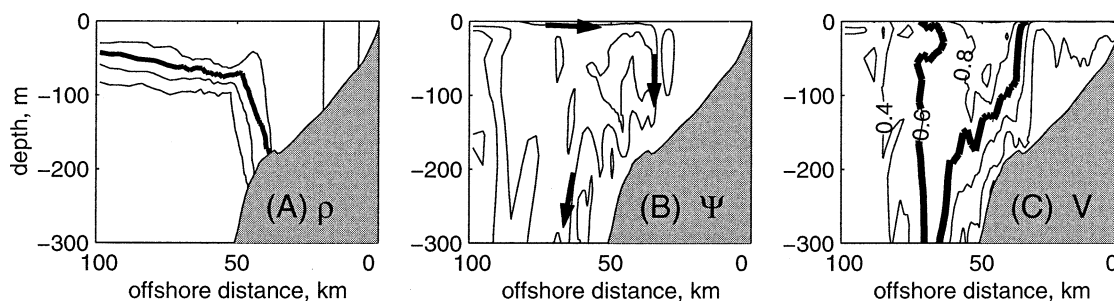

FIG. 10. Model run at day 68 during a moderate downwelling-favorable alongshore wind event: (a) density − 1000 kg m^{-3} (contour interval 0.25 kg m^{-3}, 25.5 kg m^{-3} is darkened), (b) cross-shelf streamfunction Ψ (contour interval 0.02 s^{-1}; arrows indicate sense of cross-shelf circulation), and (c) alongshore velocity (contour interval of 0.2 m s^{-1}, 0.6 m s^{-1} is darkened).
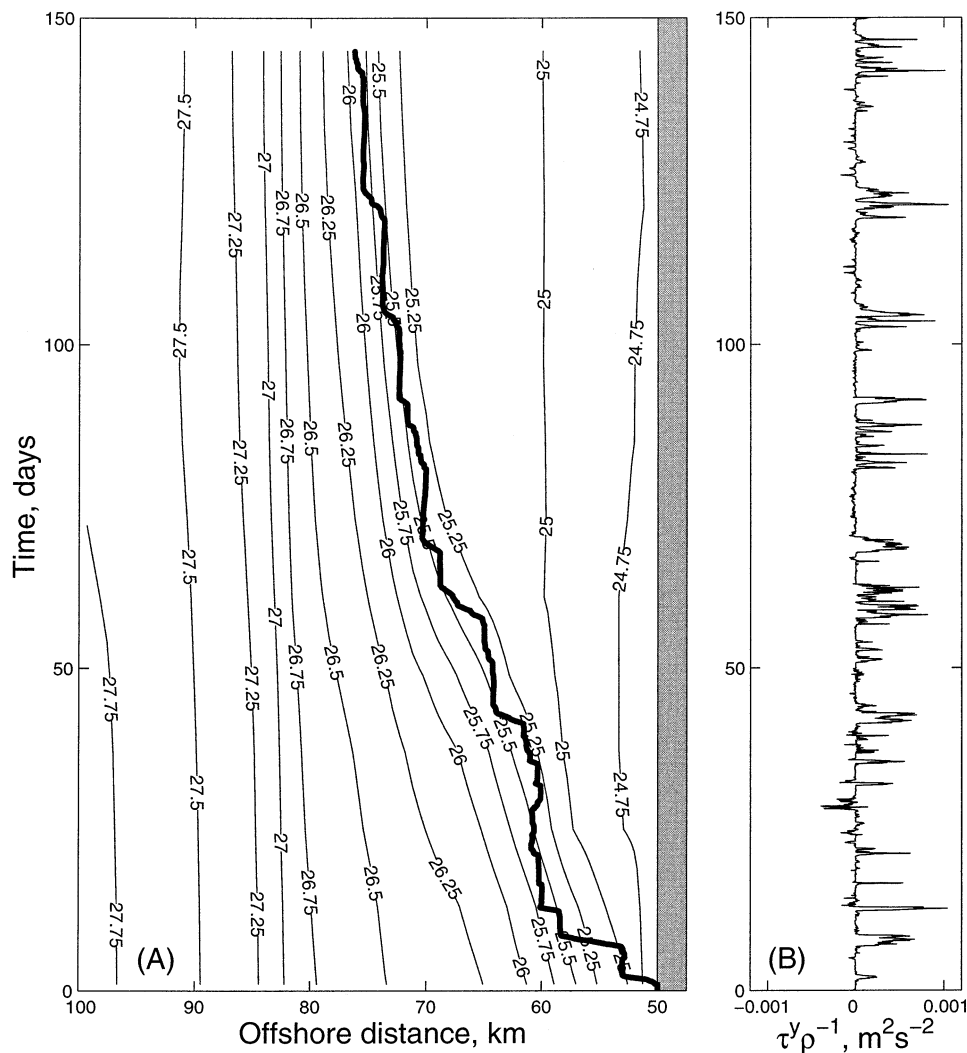
FIG. 11. The density at the bottom as a function of time and cross-shelf distance. The heavy line is the frontal displacement scaling from Austin and Lentz (2002).

pacted by the introduction of freshwater at the coast. If the behavior of the drifters was due entirely to freshwater being introduced onto the shelf through rivers, then the drifter trajectories should be influenced near the mouth of the Columbia River, the largest source of freshwater on the West Coast. However, the drifters appear to pass the mouth of the Columbia with no change in their trajectories (Fig. 7). In summary, although buoyancy effects may be present during the winter (downwelling) season, the formation of wind-driven downwelling fronts and jets is sufficient to explain the behavior of the drifters, namely rapid poleward and weak onshore movement. It may be necessary to resort to a three-dimensional model to fully resolve this issue.

b. Implications for cross-shelf transport

The results summarized in this note are an extension of the downwelling circulation results of Austin and Lentz (2002), which suggests that passive tracers advected onto the inner shelf (the region inshore of the downwelling front) remain fixed in cross-shelf position since they are vigorously mixed between the surface and bottom boundary layer, as in steady shear dispersion. In the present case, a drifter (simulated or real) remains in the surface layer and is still not significantly displaced in the cross-shelf direction, while being significantly displaced alongshore.

5. Summary

The Ekman circulation from downwelling winds does not beach drifters released during the winter season. Instead, the downwelling circulation (the bottom front, alongshore jet, and weak cross-shelf flow inshore of the front) traps them some distance offshore and advects them rapidly northward. The importance of understand-
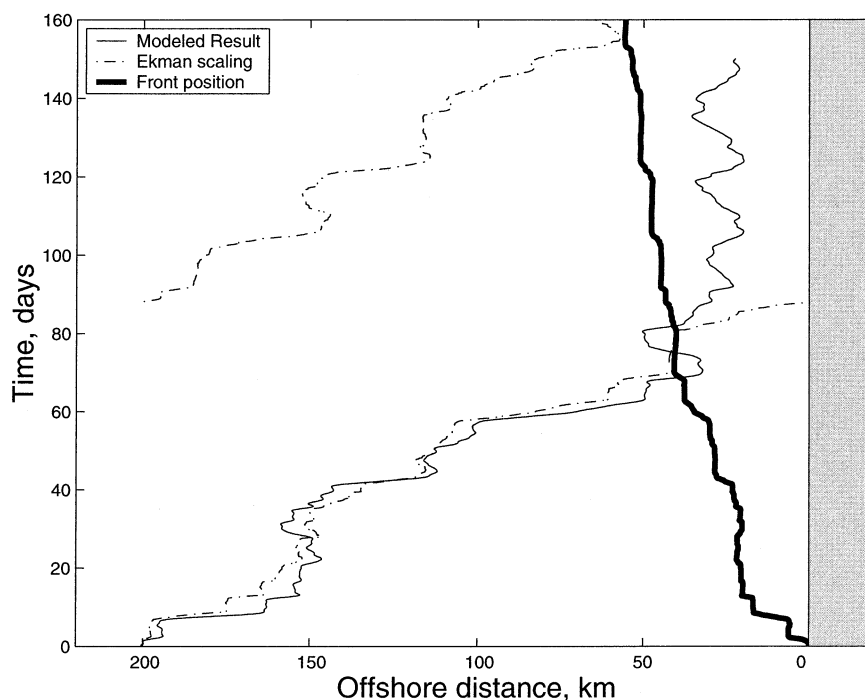
FIG. 12. A comparison of the offshore displacement of the drifter started at 200 km with the simple constant Ekman depth scaling of the displacement. The position of the simple drifter is "reset" around day 84 after it went aground. The heavy line is the scaled position of the front, as in Fig. 11.

ing cross-shelf variation in the character of the surface Ekman transport is clear from the drifter behavior, independent of the model results. The model results provide a reasonable framework for understanding the drifter behavior during downwelling conditions.

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