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Transport of surface waters from the Juan de Fuca eddy region to the Washington coast

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Abstract

A seasonal cold eddy located off the mouth of the Strait of Juan de Fuca has been implicated as an initiation site for toxic HABs affecting the Washington coast. To investigate the fate of eddy waters, a diagnostic finite element circulation model was developed for this region and the northern Washington shelf. The model was based on hydrographic data from several cruises in the summer of 1998, a year in which record levels of toxin were measured in razor clams at Washington beaches. Additional model forcing included tides and surface wind stress typical of fair weather/upwelling conditions or fall storms.

The model showed strong retention in the eddy and a preferred southeastward trajectory for model drifters leaving the eddy. ARGOS-tracked drifters released in the vicinity of the eddy in the summers of 2001 through 2003 were consistent with model results generated with 1998 data demonstrating the robust nature of the large-scale currents in this region. Model and true drifter results show that the Juan de Fuca eddy is an important source region for PNW shelf waters. Furthermore, both model and true drifters moved onshore during storms suggesting that surface waters of the Juan de Fuca eddy can impact the Washington coast.

Keywords: Juan de Fuca eddy; Harmful algal blooms; Circulation; Washington; Vancouver Island

1. Introduction

The Juan de Fuca eddy, an important component of the summer circulation off the northern Washington coast and southwestern Vancouver Island, has recently been implicated as a potential source region of toxic *Pseudo-nitzschia* blooms which impact the Washington coast (Trainer et al., 2002). Several species of diatoms in this genus are known to produce the neurotoxin domoic acid, which enters the food chain through planktivorous fish and shellfish. Surveys conducted during the

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summer of several years indicate that *Pseudo-nitzschia* in the vicinity of the Juan de Fuca eddy are more likely to produce the toxin than blooms in nearshore upwelling regions (Trainer et al., 2002).

The eddy is a cyclonic cold feature located off the mouth of the Strait of Juan de Fuca on the southern British Columbia shelf. This region is one of extremely complex bathymetry (Fig. 1). The shelf width varies from 40 to 100 km, with maximum width off the mouth of Juan de Fuca Strait. Shallow banks are separated by numerous deep canyons including the 400 m deep, ~10 km wide Juan de Fuca canyon which bisects the shelf. The canyon makes several sharp bends before entering the strait. Deep upwelled water passes through the canyon and enters the strait as a compensating flow to the surface estuarine outflow (Mackas et al., 1980).

First identified by Tully (1942), the eddy was the subject of several studies in the 1980s (Freeland and Denman, 1982; Denman and Freeland, 1985; Freeland and McIntosh, 1989). These studies showed the eddy to be a seasonal feature, developing around the time of the spring transition and declining in the fall. During this period, typical alongshore winds are from the northwest and force a seasonal mean southeastward shelf break current over the slope and outer shelf. These shelf currents are oppositely directed to the buoyancy driven Vancouver Island coastal current (VICC), which flows northwestward from the mouth of Juan de Fuca Strait adjacent to the west coast of Vancouver Island (Thomson et al., 1989;

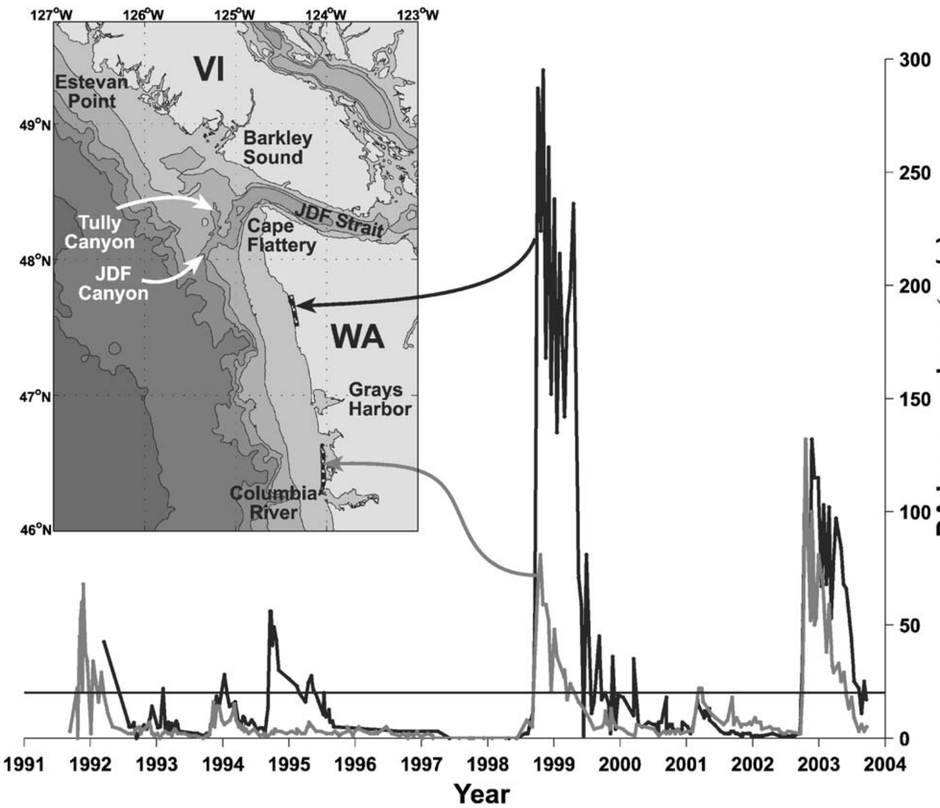

Fig. 1. Time series of domic acid measured in razor clam tissue by the WA state Department of Health at northern and southern clamming beaches. Inset shows WA and southern VI shelf bathymetry and location of places mentioned in the text. Bathymetry contours depicted here and in subsequent figures are 2500 m, 1000 m, 500 m, 180 m and 100 m.

Hickey et al., 1991). Freeland and Denman (1982) showed that the eddy was evident in the deep water on the southern British Columbia continental shelf as a cold, oxygen-poor, high-nutrient water mass. They also noted that the position of the eddy was relatively stationary with the center closely related to a northern branch of the underlying Juan de Fuca canyon, which they called the Spur Canyon (later renamed Tully Canyon, Fig. 1).

South of the eddy, off Washington, mid to outer shelf currents are typically southward and surface-intensified, associated with the seasonal mean wind-driven upwelling that occurs near the coast in summertime. Maximum equatorward flow migrates offshore as the season progresses with strongest flow occurring on the outer shelf by late summer (Hickey, 1989).

Summertime winds vary on short (3–10 days) time scales and periods of strong southward, upwelling-favorable winds are separated by periods of weak or northward winds which can reverse the direction of flow, particularly on the inner shelf (Hickey, 1989). Along shelf flow responds to these changes in local wind direction and magnitude with a lag of $\sim 1/2$ day. Upwelling near the coast and cross shelf flow in the surface Ekman layer respond to these changes more rapidly (Hickey et al., 1998). Much of the variability in summertime is a result not just of local wind changes, but of changes in winds remote to the region (Hickey et al., 1991). Significant gradients in along shelf wind stress, with stronger (typically upwelling favorable) winds to the south in spring and summer, result in the generation of coastal trapped waves. These waves propagate northward with wavelengths of hundreds to thousands of kilometers and speeds of 300–500 $km\,d^{-1}$, adding to the local wind-generated alongshore currents (Battisti and Hickey, 1984).

At the Washington coast, widespread harvesting closures have occurred at razor clam beaches due to high levels of domoic acid three times in the last 12 years—in mid to late September of 1991, 1998 and in 2002. The time series of domoic acid measured in razor clam tissue, collected by the Washington state Department of Health, is shown in Fig. 1 for both northern and southern razor clam beaches. The 1998 event was the largest ever observed at Washington beaches, with domoic acid levels in razor clam tissue reaching over 10 times the regulatory limit. Trainer et al. (2002) showed that the increase in toxin levels at the coast occurred after a period of persistent upwelling followed by a downwelling-favorable wind event with associated onshore transport. They hypothesized that the seasonal Juan de Fuca eddy is an initiation site for toxic *Pseudo-nitzschia* which impact the Washington coast, and that upwelling sites adjacent to the coast are less likely to develop toxicity.

In this paper, we examine the physical setting of the 1998 event and more recent data from Lagrangian drifters with the goal of describing pathways of surface waters from the eddy to the Washington coast under typical summer wind conditions. After a description of the data and methods in Section 2, hydrographic data from the summer of 1998 are used to describe the physical setting of the region and show the vertical structure of the eddy (Section 3). We also examine characteristics of the eddy region that differ from those in the coastal upwelling zone. Section 4 details the results of recent drifter deployments in the region of the eddy in the summers of 2001 through 2003. In Section 5, we discuss results from a diagnostic model based on the 1998 hydrographic data. Drifter and model results are then used to examine the circulation in the eddy region and to determine the conditions under which toxic *Pseudo-nitzschia* present offshore might impact Washington coast beaches.

2. Data and methods

2.1. Hydrographic data

Ship-of-opportunity data were available from several cruises between mid-June and mid-August 1998 (Fig. 2). The Canada/USA international border bisects the Juan de Fuca eddy region and surveys tend to be confined in scope to either the Washington (WA) or British Columbia (BC) shelves. The WA shelf was surveyed on two cruises during this period. On the first cruise, aboard the

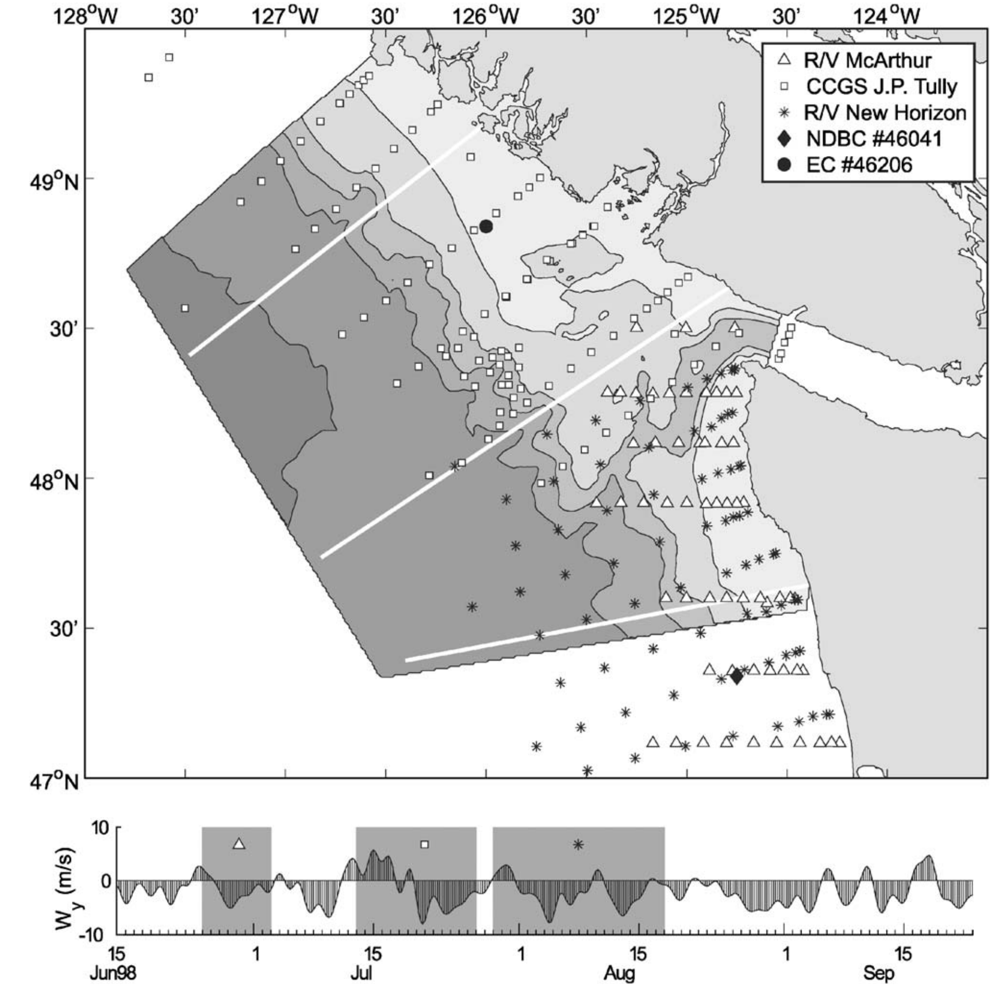

Fig. 2. CTD locations from the three summer 1998 cruises and locations of wind moorings maintained by the National Data Buoy Center (NDBC) and Environment Canada (EC). The contoured area shows the domain and bathymetry for the diagnostic model. Lines extending across the shelf mark the locations of vertical sections shown in Fig. 4. The bottom panel shows the north/south component of the wind for summer 1998, measured at the Cape Elizabeth mooring (NDBC #46041) with the timing of the three cruises shaded.

NOAA research vessel McArthur, 7 lines were sampled across the northern WA shelf between 25 June and 3 July, transiting from north to south. During this period the winds were primarily to the southeast or upwelling favorable, with maximum magnitude ~30 June (Fig. 2). The second cruise occurred between 29 July and 18 August aboard the UNOLS research vessel New Horizon. The cruise included 12 transects across the northern Oregon (OR) and WA shelves. The northern WA shelf transects, between Grays Harbor and Cape Flattery, were occupied 7–14 August. Winds were again moderately strong and upwelling favorable, with a short reversal to northward winds on 11 August (Fig. 2). A third cruise, on the BC shelf off Vancouver Island, occurred 13–27 July aboard the Canadian Coast Guard Ship J.P. Tully. Cross shelf transects were generally occupied from south to north, though additional stations around Barkley Canyon and the transect across the mouth of Juan de Fuca Strait were conducted near the end of the cruise. The southernmost five cross shelf transects were occupied between 15–20 July, a period of moderate northward winds. Upwelling favorable winds resumed on 20 July and were persistent for the duration of the cruise (Fig. 2).

Standard hydrographic data was obtained on all 3 cruises, using the Sea-Bird Electronics SBE 911plus. Processing included the use of standard Sea-Bird Seasoft processing software, comparison of data from primary and secondary sensors, comparison of pre- and post-cruise calibrations, and, in the case of conductivity, comparison with bottle samples.

Since no comprehensive survey data were available, our approach was to combine data from the 3 cruises to produce average temperature, salinity and σ_t fields for summer 1998. The CTD data were smoothed and interpolated to the model grid on level surfaces using objective analysis with correlation length scales of 40 km and a mean square noise level of 25%. Due to the sparse number of deep CTDs on level surfaces below 500 m, climatological data for the southern BC/northern WA shelf (described in Foreman et al., 2000) were incorporated. The 3-dimensional average fields were then used to examine the eddy structure and to contrast vertical sections in the eddy region with the WA and BC shelf upwelling regions. The σ_t field was also used to provide the input baroclinic pressure gradient for the diagnostic model discussed in Section 5.

2.2. Wind

Wind velocity vectors were constructed using wind speed and direction measurements obtained from observations at meteorological buoys maintained by the National Data Buoy Center (Cape Elizabeth #46041 at 47.34°N, 124.75°W) and Environment Canada (La Perouse Bank #46206 at 48.84°N, 126°W) (Fig. 2). These time series data were used both to characterize the setting of the cruises as well as to derive wind stress fields representing typical fair weather/upwelling conditions and an early fall storm. Wind stress was calculated using the drag coefficient of Large and Pond (1981). Unless stated otherwise, wind directions in the text use the oceanographic convention with wind blowing in the direction reported.

2.3. Drifters

Beginning in 2001, limited numbers of ARGOS-tracked drifters were deployed in the eddy region during the summer. Drifter models included Clearwater Instrumentation, Inc ClearSat-1 surface drifters and Brightwaters Instrument Co. models 104A and 115. The majority of the drifters deployed were in the Davis/CODE configuration, designed to accurately track the top 1 m of water (Davis, 1985). The Brightwaters models also allow for a deep drogued configuration in which a 10 m long "holey-sock" drogue is attached and centered at the desired depth. Drifters transmitted 1/2-hourly GPS position to the ARGOS satellites. These data were used to compare with 1998 model drifters as well as to illustrate onshore transport associated with fall storms.

3. Eddy spatial structure

In this section, maps of the density field for summer 1998 as well as sections across the shelf and slope are used to describe the spatial structure of the eddy and the WA and BC coastal upwelling regions. Maps of σ_t at 5, 50 and 100 m illustrate that the spatial structure of the eddy varies dramatically with depth (Fig. 3). For example, near the surface, the eddy is not a closed feature nor is it distinct from the dense water upwelled along the WA coast. Nevertheless, a broad region of dense water is located west of the mouth of the strait. At 50 m depth the eddy appears as a distinct feature centered to the northwest of the Spur Canyon. At this depth, the extent of the anomalous high σ_t water used to define the eddy has length and width scales very similar to those reported previously (Freeland and Denman, 1982), roughly 60 km by 40 km respectively. At the deepest depth shown, 100 m, the center of the density anomaly is centered at approximately the same location as at 50 m. However, the eddy at 100 m is less elongated in the alongshore direction and appears more symmetrical.

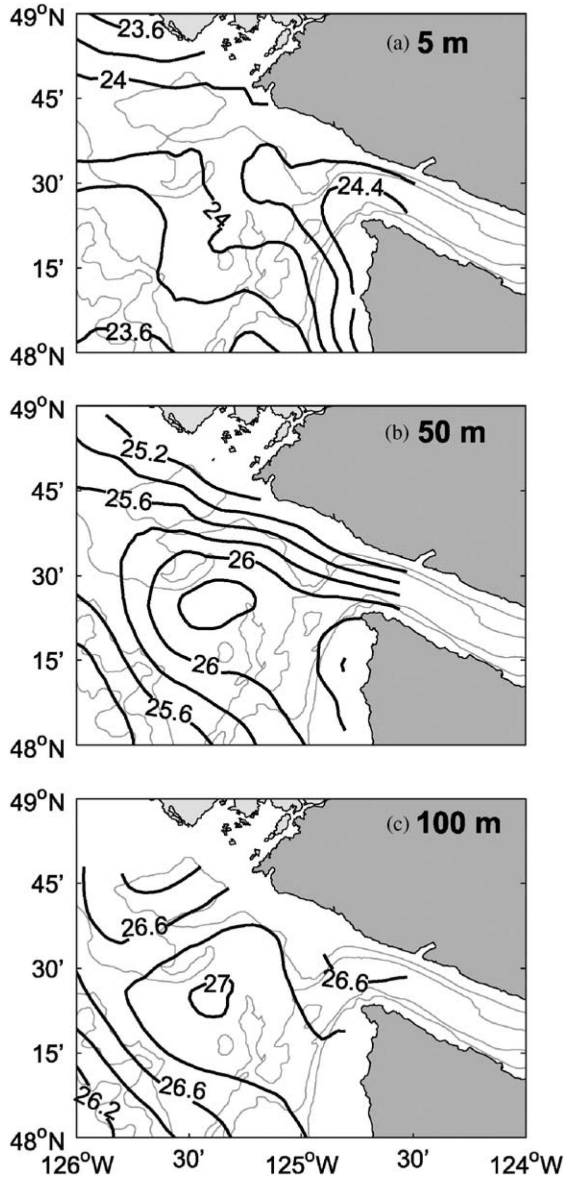

Fig. 3. σ_t at (a) 5 m, (b) 50 m and (c) 100 m, showing the extent of anomalously dense water used to define the Juan de Fuca eddy.

Vertical salinity and temperature sections across the WA shelf, the Vancouver Island shelf and in the eddy region illustrate the differences in stratification and upwelling in these regions (Fig. 4; transect locations in Fig. 2). The WA shelf section is typical of wind driven upwelling, with isotherms and isohalines sloping upwards, reaching the surface near the coast. Surface waters are highly stratified, much more so than in the northern section across the Vancouver Island shelf.

In the northern section, the VICC is evident as the relatively fresh water at the coast, out to about 40 km. Both isohalines and isotherms slope upwards across the shelf edge indicative of the southward baroclinic upwelling jet. This feature is present in all the sections, suggestive of the continuity between the VI shelf break current and the WA outer shelf currents.

In the section through the eddy, the isohalines/isotherms are dramatically domed upwards over the outer shelf (Fig. 4). In this region, the cold, salty bottom water ($<7\,^{\circ}$C, >33.8 psu) is upwelled to much shallower depths than in the WA coastal upwelling region. Although upwelled water does not reach the surface in this region, it does reach the base of the pycnocline. In contrast to the WA coast section, isohalines tend downwards near the coast of Vancouver Island, consistent with the presence of the VICC. The fresh water in the VICC appears to suppress upwelling in these data. However, the bulk of the data in this region is biased towards downwelling conditions (Section 2) and we note that upwelling has been observed to occur intermittently at the Vancouver Island coast (Hickey et al., 1991).

4. GPS-tracked drifters

In this section, Lagrangian drifters deployed in the vicinity of the Juan de Fuca eddy are used to illustrate the dominant transport pathways in this bathymetrically complex region. The similarity in drifter tracks between years provides evidence of the robust nature of circulation patterns in the region. ARGOS-tracked drifters were deployed in the summers of 2001 through 2003. The majority are surface drifter tracks, though several tracks from 5 m drogued drifters and one 20 m drogued drifter are also included and noted (Fig. 5).

In the regional-scale figure, including southern BC, WA and Oregon, the eddy is evident as a cyclonic circulation pattern off the mouth of Juan

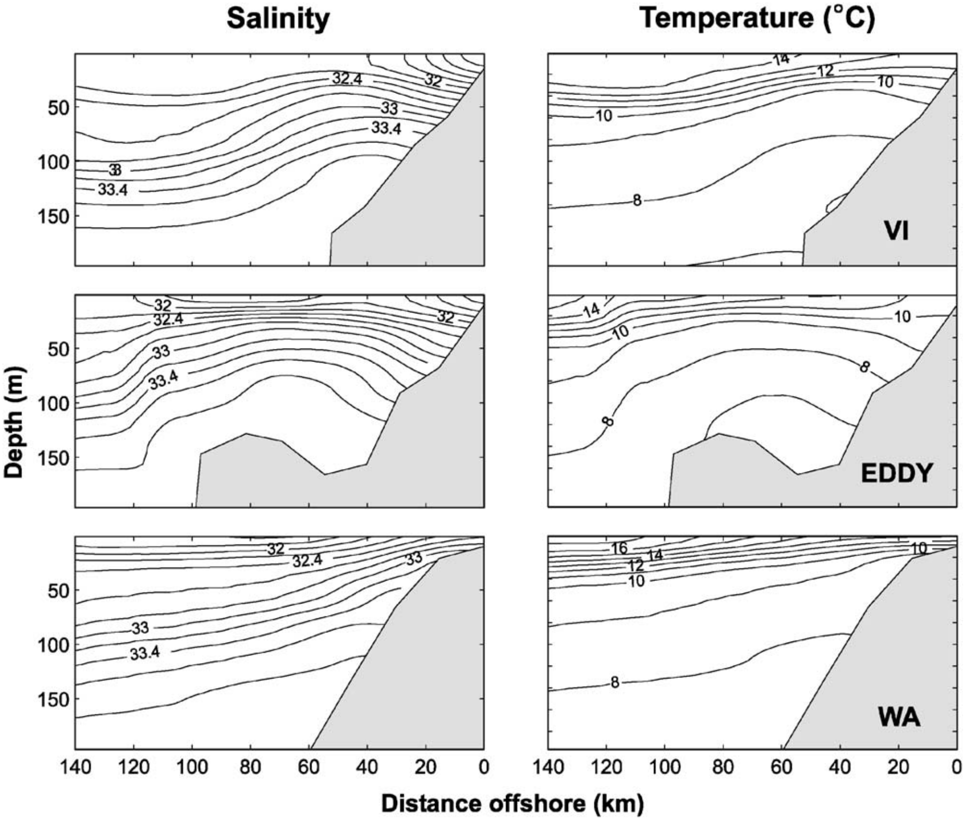

Fig. 4. Vertical sections of salinity (left panels) and temperature (right panels) across the VI and WA shelves and through the Juan de Fuca eddy region. Locations of the sections are shown in Fig. 2.

de Fuca Strait (Fig. 5). Tracks from all drifters deployed in the vicinity of the eddy illustrate the regional importance of circulation and water properties in the Juan de Fuca region. Drifters deployed near the mouth of the strait either leave to the northwest in the VICC or circulate within the eddy. Those circuiting the eddy do so in ~10–12 days. Drifters exiting the eddy leave to the southeast converging in the seasonal coastal front on the outer WA shelf. Drifters take ~20 days to transit the WA shelf from north to south. Further to the south, drifters are swept offshore as they approach Heceta Bank, OR. Thus, surface waters from this region are not only important source waters for the WA shelf but ultimately for the larger scale California Current.

An enlargement of drifter tracks in the Juan de Fuca region illustrates the spatial scales and variability of pathways in the vicinity of the eddy (Fig. 5, inset). As previously noted, the tracks are not synchronous and there is significant variability in the strength of southward winds between drifter tracks. Even so, the drifters show a coherent circulation field, demonstrating the robust nature of the currents in this region.

Two drifter tracks beginning near the mouth of the strait illustrate the presence of the VICC (Fig. 5, inset); they move northwestward along the VI coast. These drifters were deployed in early September of 2002 and 2003, drogued at 5 and 20 m, respectively. Velocities for both drifters are large near the mouth of the strait, 25–35 $cm\,s^{-1}$. However, the 20 m drogued drifter slowed as it moved north. A velocity of ~10 $cm\,s^{-1}$ was observed off Barkley Sound.

Drifters leave the eddy to the southeast and flow along the WA shelf with typical velocities of 10–30 $cm\,s^{-1}$. Maximum velocities observed on the

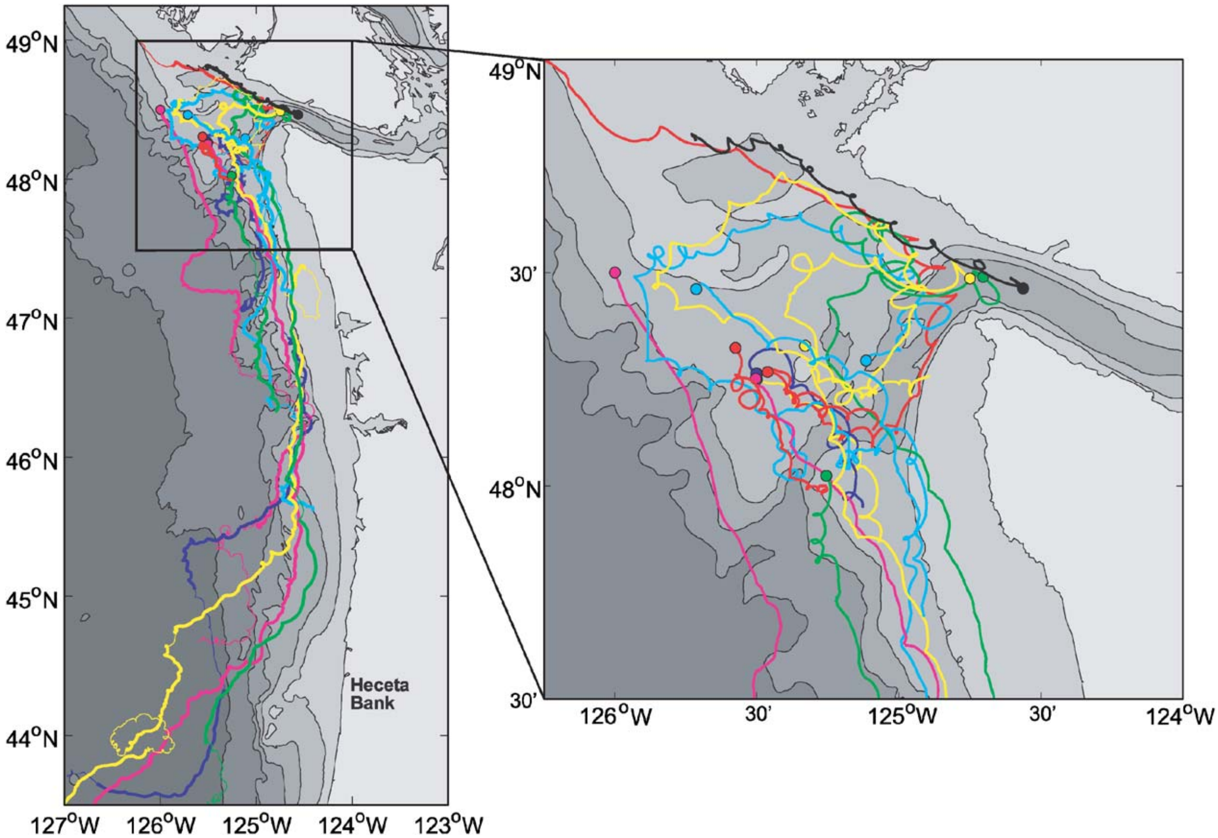

Fig. 5. Tracks of ARGOS-tracked drifters deployed in the Juan de Fuca eddy region in the summers of 2001–2003. Drifters were primarily Davis style surface drifters. Tracks from several drifters drogued at 5 m are included and are shown in red and one track from a drifter drogued at 20 m is shown in black.

shelf, greater than $40\,cm\,s^{-1}$, were from a drifter deployed in June of 2003 that took the most inshore path, between the 60 and 80 m isobaths. This drifter was on the WA shelf during a period of fairly constant and moderately strong southward winds and transited from the eddy region to south of the Columbia River in less than 10 days.

To illustrate effects of downwelling or northward winds on the transport pathways, two drifter tracks from 2001 and two from 2003 are shown in Fig. 6, along with winds for the corresponding time periods. In 2001 (Fig. 6a) drifters were deployed during a prolonged upwelling period, about a week apart. Two storms occurred while they were offshore of WA, a short reversal of about 2 days, and a longer reversal of about five days. Both drifters slowed and moved onshore slightly during the first storm. During the second reversal, the northern drifter was much further inshore and moved ~15 km onshore then reversed direction. The southern drifter moved ~45 km onshore during the same wind reversal, then began moving back offshore with the cessation of northward winds.

Two significant downwelling events also occurred in 2003 (Fig. 6b) while drifters were on the WA shelf. Both drifter tracks start on the same day during a short upwelling period. During the first storm, which again lasted approximately 2 days, the northern drifter reversed direction, whereas the southern, more offshore drifter merely slowed. They both moved somewhat onshore,

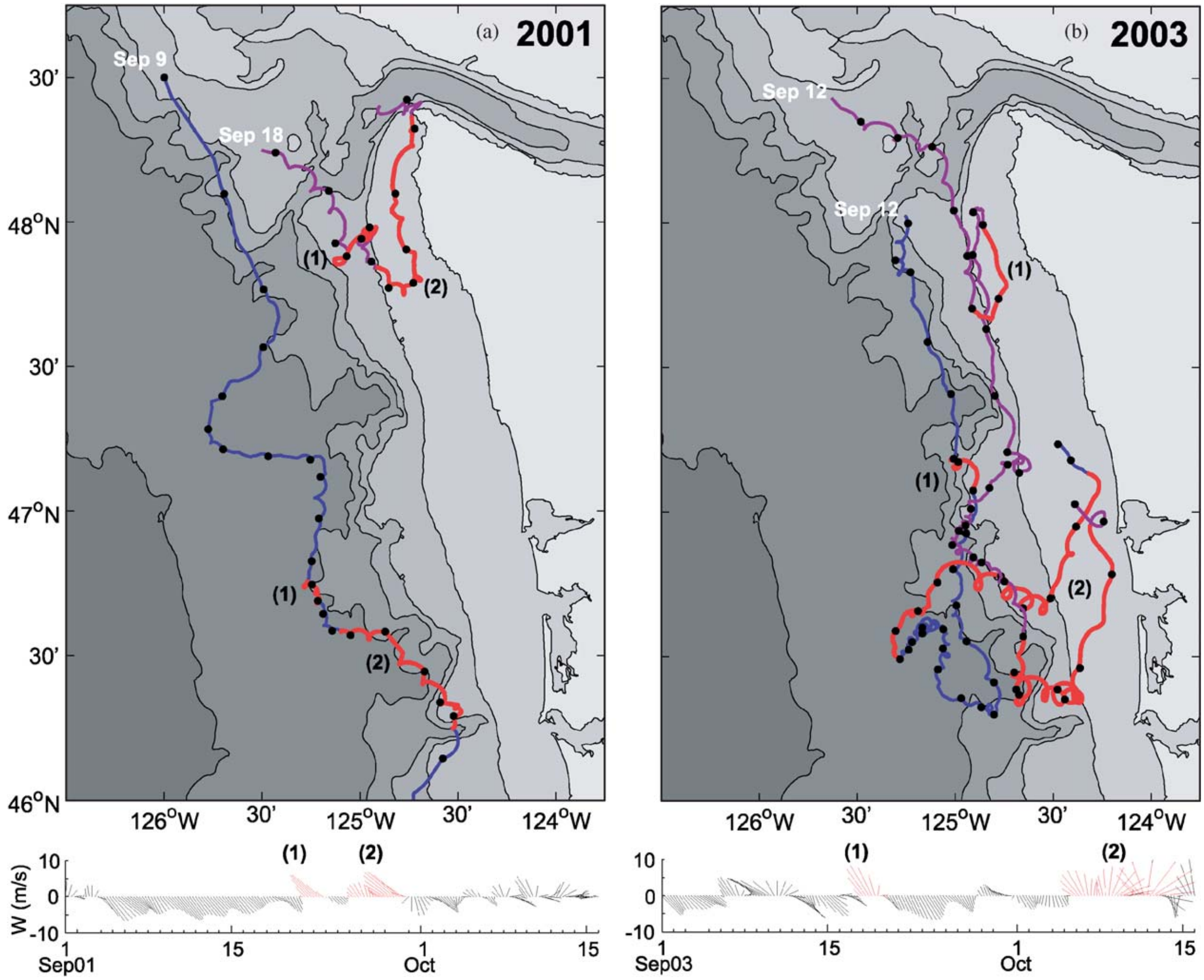

Fig. 6. Tracks of drifters deployed in the late summer of 2001 (a) and 2003 (b) showing onshore advection associated with fall storms. Wind vectors from measurements at the Cape Elizabeth mooring (NDBC #46041) are shown for the two time periods. The periods of northward winds which coincide with observed onshore movement of the drifters are marked in red on both the wind time series and drifter track.

~7 km. During the second, week long reversal, both drifters moved onshore ~30–60 km and eventually reversed direction.

5. Diagnostic model

5.1. Description

A diagnostic finite element model, FUNDY5, was used to examine the circulation in the eddy region during the summer of 1998 in more detail. The model, described in Naimie and Lynch (1993) with modifications described in Foreman et al. (2000), has been used for numerous diagnostic simulations around Georges Bank (Lynch et al., 1992; Naimie et al., 1994) as well as to compute initial conditions for semiprognostic model runs (Foreman et al., 2000). The linearized 3-dimensional shallow water equations are solved on a triangular grid yielding a velocity field and sea surface elevation. The hydrostatic and Boussinesq approximations are made, with eddy viscosity closure in the vertical. Solutions are assumed to be periodic in time; steady responses are the limiting case of zero frequency.

The model domain is shown in Fig. 2. The western boundary is seaward of the 2400 m isobath with the northern boundary extending approximately 140 km offshore of Estevan Point midway up Vancouver Island. The southern boundary extends about 170 km offshore of northern Washington. The finite element grid allows for increased resolution over the shelf break and canyons. Grid resolution varies from as small as 170 m up to 11 km near the western boundary.

The linearity of FUNDY5 allows final velocities to be calculated as the summation of baroclinic and barotropic components from separate model solutions. Four tidal constituents, M_2, S_2, K_1, and O_1, were computed first using elevation boundary conditions obtained from Foreman and Thomson (1997). The flows due to the baroclinic pressure gradient were forced with the 3D σ_t field described earlier. Elevation specified boundary conditions were determined iteratively for the southern and western boundaries such that there was no geostrophic bottom flow normal to the boundary (Naimie et al., 1994). The northern boundary elevations were also chosen iteratively, such that the vertically averaged flow was approximately normal to the boundary (using the geostrophic radiation condition option in FUNDY5). The Juan de Fuca Strait entrance was treated as a closed boundary. Wind driven flows were forced with a spatially constant wind stress representative of typical 1998 conditions for two cases—specifically an upwelling wind velocity of $7\,\mathrm{m\,s^{-1}}$ at 310 °T and $7\,\mathrm{m\,s^{-1}}$ at 180 °T for a fall storm (here headings specify the direction from which the wind blows). Boundary elevations were interpolated from a model run on a larger domain with the same wind forcing. It should be noted that the baroclinic solution alone may already incorporate part of the adjustment to the wind driven event-scale sea surface slope.

To allow visualization of the transport pathways, model flow fields were seeded at the surface with drifters using DROG3D (Blanton, 1992). DROG3D allows particles to be advected horizontally and vertically on a 3D finite-element grid by one or more velocity fields using a fourth-order Runge–Kutta integration scheme.

5.2. Results

The eddy is clearly apparent in the modeled sea surface height as a relative sea level minimum (Fig. 7). Model sea surface height resulting from forcing due to the baroclinic pressure gradient varies by about 8 cm from the inside to outside of the eddy with maximum surface currents of $\sim 40\,\mathrm{cm\,s^{-1}}$ at the western edge of the eddy. Sea surface height also illustrates clearly the regional continuity of the seasonal upwelling front.

The signature of dense water upwelled at the WA coast is also very evident in the modeled sea surface height field (Fig. 7). SSH decreases towards the coast over a broad 100 km wide region by ~15 cm. The strongest gradient is observed near the shelf edge, about 35 km offshore, resulting in maximum southward velocities of $\sim 25\,\mathrm{cm\,s^{-1}}$ in that region.

To examine circulation and transport of surface waters from the eddy region we consider two cases, representing typical summer upwelling and downwelling conditions. In the first case, model forcing includes the fixed baroclinic pressure gradient

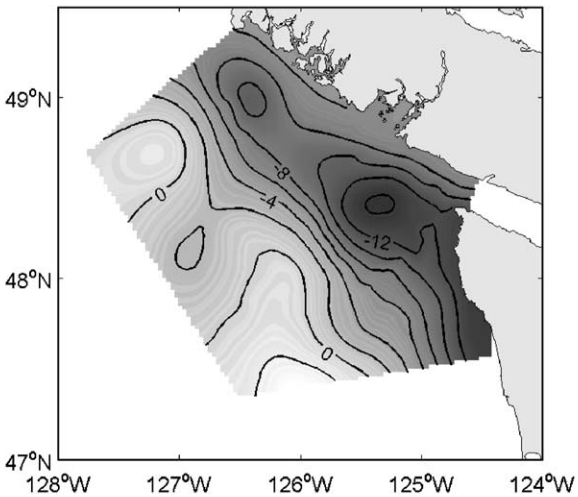

Fig. 7. Model sea surface height (cm). Model forcing includes pressure gradient from 1998 density field and elevation specified boundary conditions (see text).

derived from the 1998 summer average density field, tides, elevation specified boundary conditions and a typical summer upwelling-favorable wind stress. In the second case, we instead apply a downwelling-favorable wind stress.

Results from seeding model flow fields with surface drifters in the eddy region are compared for the upwelling and downwelling cases (Fig. 8). In the upwelling case, model drifters released into this circulation field show strong retention within the Juan de Fuca eddy; drifters on the outer edge take about 10 days to circuit the eddy while those released near the center remain trapped. Drifters exiting from the eddy tend to the southeast, roughly following the shelf contours.

In the downwelling case, model drifters again show tight retention in the eddy, with a stronger recirculation at the southern edge (Fig. 8). Model drifters within the eddy remain trapped or exit to the north. However, the addition of the northward wind stress results in onshore flow in a surface Ekman layer and drifters originating south/southwest of the eddy move onshore and reverse direction near the coast.

These results suggest it is only through a combination of upwelling and downwelling wind conditions that surface waters from the eddy may impact the WA coast: model drifters exit the eddy to the southeast during upwelling periods and are then advected onshore during subsequent downwelling periods.

To assess model results, model velocities for the upwelling case are compared with real along-track 48-h low pass filtered drifter velocities from 2001–2003 (Fig. 9). To facilitate the comparison, only portions of drifter tracks coinciding with upwelling favorable winds were selected. The model velocities were selected from the nearest model node point to the 12-h drifter positions. Model and real drifter patterns and velocity magnitudes are surprisingly similar. Both show the eddy and a strong shelf break surface current. The eddy center is similarly located in both real and model drifter pathways. The similarity

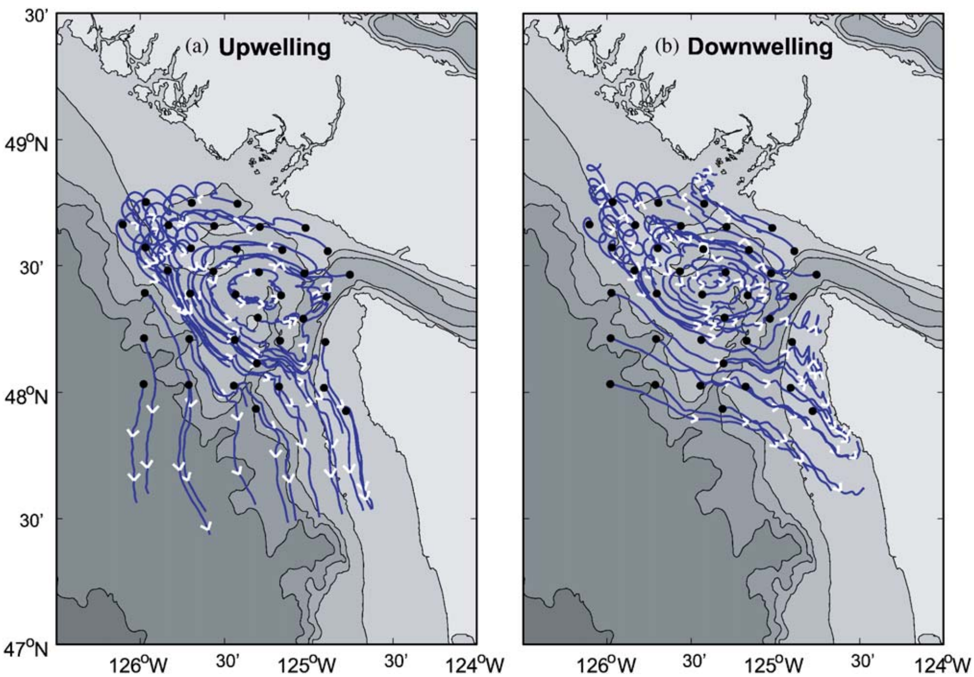

Fig. 8. Tracks of hypothetical surface drifters seeded into the model flow fields for the upwelling (a) and downwelling (b) cases. Black dots show where drifters were introduced; white directional arrows are separated by 48-h intervals.

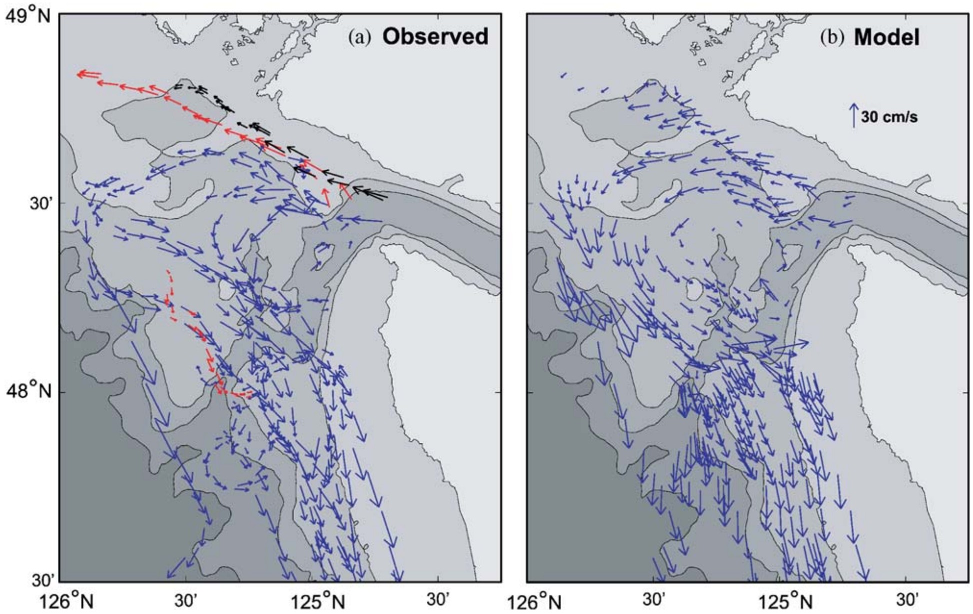

Fig. 9. (a) Along-track 48-h low pass filtered drifter velocities at 12-h intervals for portions of real drifter trajectories during upwelling conditions. Drifters drogued at 5 and 20 m depths are colored as in Fig. 5. (b) Model velocities from the ''upwelling'' case (no tides) selected at the nearest model node points to the 12-h drifter positions.

between 1998 summer model results and 2001–2003 summer drifter tracks further supports our observation that the large-scale features in this region are robust. The only feature that is not well represented by the model is the VICC: model flow along the southern Vancouver Island coast is weak and more westward than observed currents. This is likely because the Juan de Fuca and southern boundary conditions should include barotropic components analogous to those described in Foreman et al. (2000).

6. Discussion and summary

In this paper, we have combined results from a diagnostic model of circulation for the summer of 1998 with tracks from surface drifters deployed in recent summers to describe the surface circulation on the southern BC and northern WA shelves and the connection between them. Previous studies have found that freshwater outflow from the Strait of Juan de Fuca generally travels poleward along the coast of Vancouver Island as the buoyancy driven VICC (Thomson et al., 1989; Hickey et al., 1991). Data presented here, from drifters released near the mouth of the strait, demonstrate an alternate pathway in which surface waters leaving the strait join the Juan de Fuca eddy and are then advected southward over the WA shelf. Though several previous studies also showed surface waters exiting the eddy to the south (Crawford, 1988; Venkatesh and Crawford, 1993), the role of Juan de Fuca Strait water on the WA/OR shelves has not been considered in detail. It appears that outflow from the strait forms an important component of Pacific Northwest shelf water, and ultimately of the California Current when it is swept offshore near Heceta Bank, OR. Model and drifter results also demonstrate the regional connection between the VI outer shelf/slope and the WA-OR shelf via the large-scale seasonal coastal upwelling jet.

Hickey et al. (1991) measured currents at a mooring situated off Barkley Sound, at the northern edge of the eddy. Fluctuations at this location were more variable than at locations further downstream in the VICC and had two dominant directions: northwestward and southwestward. The southwestward fluctuations, in which surface waters from the strait join the eddy, were found to follow periods of particularly strong outflow from the strait. Due to fortnightly tidal modulation of the freshwater export, the VICC may be described as a series of buoyant plumes superimposed on a steadily forced seasonal mean current (Hickey et al., 1991). At the present time we do not have enough data from drifters deployed near the mouth of the strait to calculate correlations between drifter paths and strait outflow. However, it is likely that strong outflow periods, with associated southwestward currents off Barkley sound, would result in surface strait waters forming a larger component of WA shelf water.

During summer fair-weather/upwelling conditions, model and real drifter results show a residence time within the eddy of about 10 days for drifters transiting the perimeter. Drifters exit the eddy to the southeast and move along the shelf with typical speeds of $\sim 20\,\mathrm{cm\,s^{-1}}$. Despite the variability in alongshore currents in this region due to changes in both local and remote forcing, numerical and true drifter circulation patterns show remarkable similarities between years. The presence of the topographically confined eddy off the mouth of the strait contributes to a robust large-scale circulation pattern in this otherwise complex region.

Model and real drifter pathways illustrate that HABs maintained offshore can readily be transported to the inner WA shelf during periods of downwelling. During such events, currents on the inner shelf reverse direction from southward to northward. Farther offshore, the seasonal mean currents in the upwelling jet are strong enough to prevent north–south current reversals even in the surface Ekman layer, although onshore transport is observed. The rapid response in north–south direction to the local wind forcing occurs on the shallow inner shelf where surface and bottom Ekman layers likely interact. Austin and Lentz (2002) have suggested that the nearshore region may act as a barrier to cross shelf transport: stratification disappears during downwelling and cross-shelf transport becomes insignificant. Although no real drifters in this study landed on the beach, in July 2004 several drifters deployed during upwelling on the WA/OR coast subsequently came ashore during downwelling (CoOP RISE program, unpublished data). HABs data, water properties at coastal stations and drifter tracks all show that offshore water does reach the WA coast during downwelling events. Although the exact mechanism remains unclear, we note that the WA inner shelf in summer is frequently strongly stratified due to the presence of Columbia plume water (Hickey et al., 2005).

Multi-year time series of DA on the WA coast show significant interannual as well as month to month variability (Fig. 1). This may be due in part to variability in the occurrence of toxic blooms offshore of the coast. The factors leading to the production of toxin are being addressed in ongoing field studies. Variability in the DA time series may also be due to variability in transport mechanisms to the coast. In this paper we have addressed one important component leading to such variability: the occurrence of onshore transport associated with northward winds in modestly strong fall storms. We hypothesize that long term variability in HABs delivery to the coast may be related to the timing of periods of upwelling, during which patches or streamers of toxic algae move southward along the shelf, and the strength and exact timing of downwelling events that can move such patches all the way to the WA beaches. This hypothesis will be resolved in ongoing modeling efforts.

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