

Influences of the Juan de Fuca Eddy on circulation, nutrients, and phytoplankton production in the northern California Current System

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[1] A diagnostic circulation model and water mass analyses are used to examine variability in the structure and circulation of the Juan de Fuca Eddy, a highly productive region at the northern end of the California Current. Results from three years of field studies demonstrate that the eddy increases in spatial extent from early to late summer as the vertically averaged contribution of California Undercurrent source water grows from ~60% in June to ~80% in September. Typical near-surface eddy radii range from ~15 km in the early summer to ~30 km in September and increase with depth. Below 100 m, eddy radii are ~40 km. Fresher water, associated with the estuarine outflow from the Juan de Fuca Strait, is advected around the eddy margin. During southward wind conditions, the combination of cyclonic geostrophic flow and wind-driven currents in the surface Ekman layer cause the eddy to be “leaky” on its southern perimeter. Eddy surface circulation becomes more retentive (up to ~32 d observed) during periods of weak winds or frequent northward reversals. The presence of the eddy facilitates large inputs of dissolved inorganic nutrients into the region through two mechanisms: doming of California Undercurrent water within the eddy and enhanced cross-shelf advection of Juan de Fuca Strait outflow. The combination of these sources results in a persistent, broad (100 km offshore) region of elevated macronutrients. The retentive circulation patterns combined with persistent nutrient supply may favor the development of toxigenic diatom blooms of *Pseudo-nitzschia* species in this region.

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1. Introduction

[2] The Juan de Fuca Eddy region, located offshore of northern Washington and southern Vancouver Island, British Columbia has been identified as a site of high phytoplankton biomass [Trainer *et al.*, 2002], elevated primary productivity [Marchetti *et al.*, 2004], and enhanced higher trophic level biomass [McFarlane *et al.*, 1997]. The region lies at the northern (upstream) end of the California Current, a well-described eastern boundary current system [Hickey, 1979; Hickey, 1998]. Although this region is subjected to the same large-scale seasonal wind patterns as the rest of the U.S. West Coast, and hence undergoes episodic wind-driven upwelling throughout the summer, the magnitude of the upwelling winds decreases to the north [Hickey, 1979]. However, highest productivity occurs

off the coasts of Washington and southern British Columbia despite the northward decrease in upwelling favorable wind intensity [Hickey and Banas, 2003; Ware and Thomson, 2005].

[3] Ware and Thomson [2005] attribute the increased productivity in this region in part to the substantial, year-round freshwater inputs from the Columbia and Fraser rivers, which they suggest leads to increased stability of the upper water column and increased supply of land-derived nutrients. The Fraser River may be particularly important to the Juan de Fuca Eddy region as it is the primary freshwater source driving an estuarine circulation in the straits of Georgia and Juan de Fuca. The deep, nutrient-rich oceanic waters entering Juan de Fuca Strait mix upwards in shallow regions of high tidal currents in the eastern strait and are entrained into the outflowing surface waters [Mackas *et al.*, 1980]. This outflow onto the shelf is at least an order of magnitude greater than the river discharge.

[4] On the southern Vancouver Island shelf, this estuarine entrainment of deep, nutrient-rich water in Juan de Fuca Strait is thought to be the dominant contributor to the dynamics of nutrient supply and subsequent plankton pro-

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duction [Mackas *et al.*, 1980]. Although outflow from the strait is typically described as flowing to the north as the Vancouver Island Coastal Current [Thomson *et al.*, 1989; Hickey *et al.*, 1991], studies of water mass properties [Mackas *et al.*, 1987] and circulation [Crawford, 1988; MacFadyen *et al.*, 2005] show considerable cross-shelf transport of the Juan de Fuca effluent. This cross-shelf export is largely dependent on the presence of a quasi-permanent, cyclonic eddy off the mouth of the strait.

[5] This eddy, termed the “Juan de Fuca” or “Tully” Eddy, was first identified by Tully [1942]. It is a seasonal, topographically confined feature which develops around the time of the spring transition and declines during the fall [Freeland and Denman, 1982]. During this time, typical along shelf winds are from the northwest and force a seasonal-mean, southeastward-flowing, baroclinic current over the slope and outer shelf. Nearshore, the buoyancy-driven Vancouver Island Coastal Current flows to the northwest. When the eddy is present, it is apparent in the deep water on the continental shelf as a cold, oxygen-poor, high-nutrient water mass [Freeland and Denman, 1982]. The shelf flow, or the eddy itself, is believed to interact with the underlying Juan de Fuca canyon system facilitating the upwelling of water from extreme depth (>400 m) onto the continental shelf [Freeland and Denman, 1982; Freeland and McIntosh, 1989]. Recent modeling studies by Foreman *et al.* [2008] indicate that upwelling off Cape Flattery may be involved in eddy generation. In their simulations, upwelling is enhanced in this region due to the proximity of the Juan de Fuca canyon. This enhanced upwelling leads to a dome of dense water that grows westward and detaches to form the eddy after reaching a sufficiently large diameter. Upwelling within the eddy is a second, potentially important nutrient source to the region.

[6] Recent studies have indicated that the eddy is an initiation site for toxic *Pseudo-nitzschia* blooms which negatively impact key Washington state benthic fisheries, such as recreationally harvested razor clams (*Siliqua patula*) [Trainer *et al.*, 2002]. In 2002, a 5-year program, Ecology and Oceanography of Harmful Algal Blooms-Pacific Northwest (ECOHAB-PNW), was initiated to examine the physiology, toxicology, ecology, and oceanography of toxigenic species of diatoms belonging to the genus *Pseudo-nitzschia* located off the Pacific Northwest coast. In this paper, we present data from three years of field studies conducted as part of the ECOHAB-PNW project. These multidisciplinary surveys, which sampled areas influenced by Juan de Fuca Strait, the Juan de Fuca Eddy, and the coastal upwelling region off the Washington coast, comprise the most comprehensive regional data set to date. One of these surveys (September 2004) coincided with the highest concentrations of *Pseudo-nitzschia* cells and its associated neurotoxin, domoic acid, ever measured in this region [Trainer *et al.*, 2008].

[7] We begin by describing the data and analysis methods, which include the use of a diagnostic circulation model and a water mass composition analysis (section 2). In section 3, the patterns and variability observed over the three years of regional surveys are discussed. In section 4, we use both the circulation model and the water mass analysis as tools to examine variability in the structure, water properties, and circulation in the eddy. Finally, in section 5, we illustrate the salient, regional effects of the eddy and how they are

modified by the observed variability in the eddy structure and circulation. In particular, we examine the role of the eddy in enhancing macronutrient supply to the northern California Current both by direct upwelling into the eddy and through advection of nutrient-rich outflow from Juan de Fuca Strait. We then examine the distributions of phytoplankton biomass (as chlorophyll *a*) within the eddy region in relation to these nutrient inputs. Finally, we address characteristics of the eddy that may be important to the development and sustenance of toxic blooms of *Pseudo-nitzschia* species.

2. Data and Methods

2.1. ECOHAB-PNW Cruise Data

[8] Data presented in this paper are from the first three field seasons of the ECOHAB-PNW project, the summers of 2003–2005. In 2003, two multidisciplinary cruises of approximately three weeks duration were conducted in early and late summer (2–23 June; 30 August to 19 September) aboard the R/V Wecoma. In September 2004 (8–28), the sole cruise for the second field season took place aboard the R/V Atlantis. Early and late summer cruises were also conducted in 2005 (7–27 July; 2–22 September) aboard the R/V Atlantis and R/V Melville, respectively. During each of the five cruises, we sampled the entire survey grid (Figure 1) over a 6–7 d period of relatively steady winds (Figure 2).

2.1.1. Hydrographic Data

[9] Hydrographic data were collected using a Sea-Bird Electronics SBE 911 *plus* Conductivity, Temperature, and Depth (CTD) system with dual temperature and conductivity sensors mounted on a rosette equipped with Niskin bottles. Data processing included the use of standard Sea-Bird processing software, comparison of data from primary and secondary sensors, comparison of pre- and postcruise calibrations and, in the case of salinity, comparison with bottle samples.

2.1.2. Phytoplankton Biomass

[10] At each station, surface samples were analyzed for phytoplankton biomass as chlorophyll *a* (Chl *a*) using either the acidification (2003 cruises [Parsons *et al.*, 1984]) or nonacidification (2004 and 2005 cruises [Welschmeyer, 1994]) *in vitro* fluorometric analyses after filtration onto Whatman GF/F filters (0.7 μ m nominal pore size). Samples were extracted at sea in 90% acetone for ~24 h at –20 to –80°C. Fluorescence was subsequently measured with a Turner Designs 10AU fluorometer calibrated at the beginning of each cruise with pure Chl *a* (Turner Designs).

2.1.3. Nutrients

[11] Water samples for dissolved inorganic nutrient analyses were collected at multiple depths from surface to near-bottom at the two inshore stations of each survey line and at every second station continuing offshore. Unfiltered samples were collected in polypropylene tubes and analyzed for nitrate plus nitrite ($\text{NO}_3^- + \text{NO}_2^-$; hereafter referred to as nitrate), orthophosphate (PO_4^{3-}), and silicic acid ($\text{Si}(\text{OH})_4$) with a Lachat QuikChem 8000 Flow Injection Analysis system using standard colorimetric techniques [Smith and Bogren, 2001; Knepel and Bogren, 2002; Wolters, 2002, respectively].

2.2. Drifters

[12] Lagrangian ARGOS-tracked drifters were deployed during all five cruises. Drifter models included Clearwater

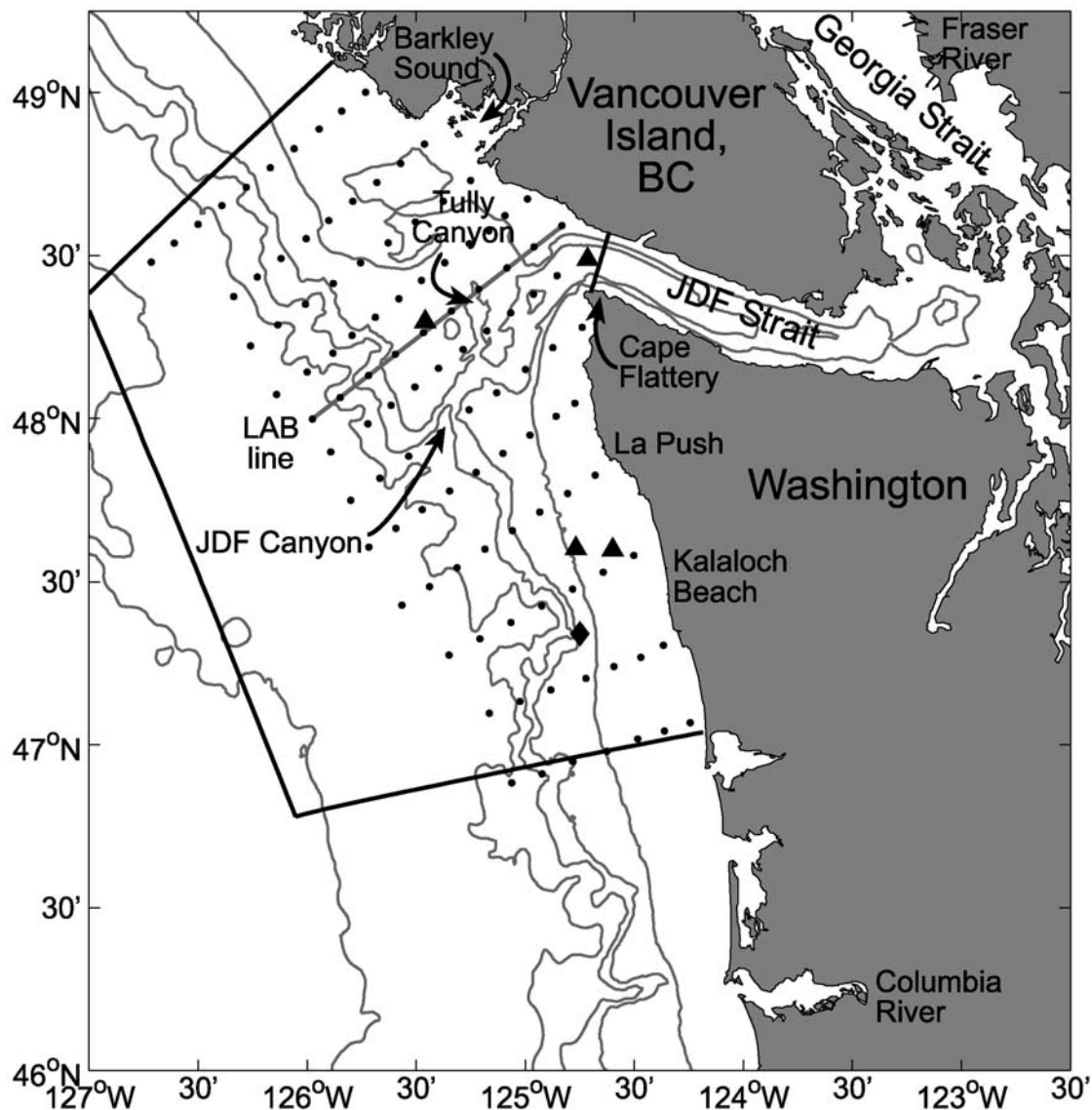


Figure 1. ECOHAB-PNW survey grid and location of moored arrays (black triangles). The location of the National Data Buoy Center's Cape Elizabeth wind buoy is also shown (black diamond). Bathymetry contours shown are 2500 m, 1000 m, 500 m, 180 m, and 100 m. The heavy black line designates the diagnostic model grid boundary.

Instrumentation, Inc. ClearSat-1 surface drifters, and Brightwaters Instrument Co. models 104A and 115. These drifter models were designed according to Davis/CODE configuration to accurately track the upper 1 m of the water column [Davis, 1985]. Drifters transmitted 1/2-hourly GPS position to the ARGOS satellites.

2.3. Moorings

[13] Moorings were deployed on the Washington shelf as a component of the ECOHAB-PNW program during all three field seasons (Figure 1). The three primary moored arrays were located at the mouth of Juan de Fuca Strait, on the northern Washington shelf west of the Tully Canyon, and at midshelf off Kalaloch Beach. The Kalaloch beach mooring was repositioned slightly inshore (~13 km) in 2005. The mooring design generally consisted of a toroidal surface buoy supporting a variety of sensors throughout the

water column. Data included here are from a Sea-Bird MicroCAT 37 (T) at 7 m above bottom, and a Sea-Bird 16 (C,T) and InterOcean S4 current meter at 4 m. Sampling rates varied on the instruments but were typically ≤ 30 min. Data were edited for spikes and averaged to hourly values. These data were low-pass filtered to remove higher frequency signals such as diurnal and semidiurnal tides using a cosine-Lanczos filter with a half power point of 46 h and then decimated to 6 h values.

2.4. Wind and Upwelling Indices

[14] Time series of wind velocity obtained from a buoy on the Washington shelf are used to derive upwelling indices that characterize environmental conditions, both seasonally and during the individual surveys. Wind data are from the Cape Elizabeth meteorological buoy maintained by the National Data Buoy Center (#46041 located at

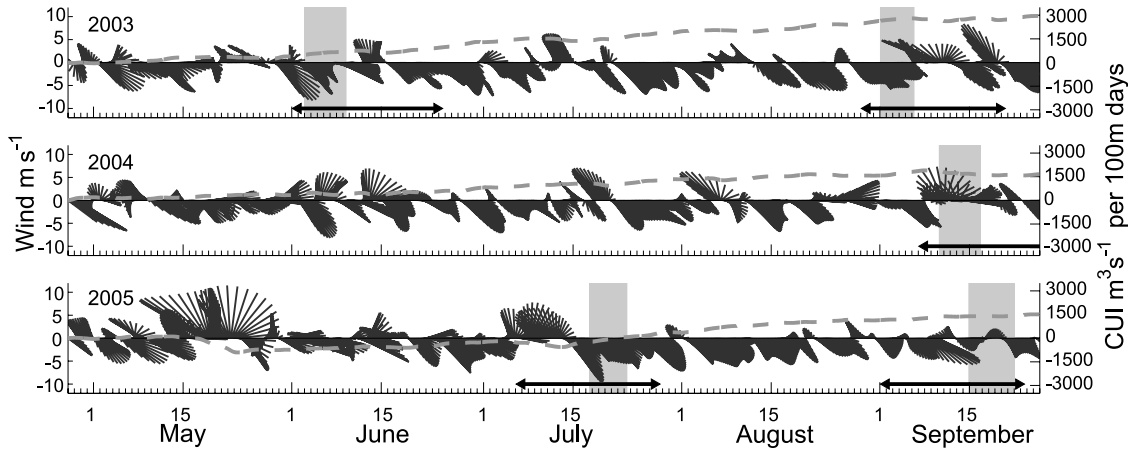


Figure 2. Wind vectors for the summers of 2003–2005 measured at the Cape Elizabeth buoy. The timing of the ECOHAB-PNW surveys (shaded) and cruises (arrows) is also shown. The dashed line is an upwelling intensity index $\left(\frac{\tau^y}{\rho f}\right)$ integrated from 27 April (see text for details).

47.34°N, 124.75°W, see Figure 1). For a seasonal index, the wind-driven cross-shelf Ekman transport is integrated over the upwelling season,

$$\int_0^t \frac{\tau^y}{\rho_0 f} dt,$$

where τ^y is the north-south component of wind stress, ρ_0 is a reference density, f is the Coriolis parameter, and t is time. The upwelling season at this latitude is defined from a climatological mean to occur from 27 April to 26 September [Schwing *et al.*, 2006]. A second, “event-scale” index is calculated by integrating the cross-shelf Ekman transport convoluted with an exponential decay [Austin and Barth, 2002],

$$W_k(t) = \int_0^t \frac{\tau^y}{\rho_0 f} e^{(t'-t)/k} dt',$$

where k is a relaxation timescale. Austin and Barth [2002] found a strong relationship between the integrated wind stress and the position of the upwelling front off Oregon for values of k between 5–12 d. We use their optimal value of 8 d. This index is utilized to compare upwelling intensity among surveys.

2.5. Diagnostic Model

[15] A diagnostic finite element model, FUNDY5, is used to examine the circulation during the cruise periods. The model, described by Naimie and Lynch [1993], with modifications described by Foreman *et al.* [2000], has been used for diagnostic simulations around Georges Bank [Lynch *et al.*, 1992; Naimie *et al.*, 1994] and previously in the Juan de Fuca Eddy region [Foreman *et al.*, 2000; MacFadyen *et al.*, 2005]. The model solves the linearized three-dimensional shallow water equations 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.

[16] The model domain encompasses the survey region (Figure 1). The use of triangular grid elements allows for increased resolution over the shelf break and canyons; the grid resolution varies from slightly less than 400 m up to ~11 km seaward of the shelf break. The model is forced with the baroclinic pressure gradient arising from the three-dimensional density field. For each survey, the CTD data are 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% [e.g., Denman and Freeland, 1985]. Because of a limited number of deep CTDs, we include regional climatological data (described by Foreman *et al.* [2000]) below 500 m. A transect across the mouth of Juan de Fuca Strait is also included from the climatology as the survey grid did not adequately resolve this region. Boundary conditions are specified identically to MacFadyen *et al.* [2005]: a geostrophic radiation condition on the northern boundary, zero bottom-flow normal to the western and southern boundaries, and a closed Juan de Fuca Strait boundary.

2.6. Least Squares Fit Water Mass Analysis

[17] The Optimum Multiparameter (OMP) analysis method can be used to find the mixture of source water types that best describes the composition of water masses. OMP analysis is capable of resolving water mass mixing on regional scales and has been used previously in this region [Mackas *et al.*, 1987; Masson, 2006]. The analysis requires observations of water mass parameters (we use temperature, salinity, and concentrations of oxygen, nitrate, silicic acid, and orthophosphate). From these observations, OMP analysis calculates the contributions from predefined source water types by finding the best linear mixing combination which minimizes the residuals in a nonnegative, least squares sense. A mass conservation condition adds an additional constraint that requires the fractional contributions from all sources add up to near unity. The various parameters are given weights to reflect differences in measurement accuracy and environmental variability; we use a diagonal weight matrix based on the parameter

variability in the source region [Tomczak and Large, 1989]. For more comprehensive details on the method see Mackas *et al.* [1987] and Tomczak and Large [1989]. Source water definitions are similar to those used by Mackas *et al.* [1987] and are described in section 4.2.

3. ECOHAB-PNW Surveys: Seasonal Patterns and Interannual Variability

3.1. Early Summer Surveys

[18] The two early season ECOHAB-PNW surveys (3–9 June 2003 and 17–23 July 2005) were conducted during periods of strong upwelling-favorable winds (Figures 2 and 3). In both cases, cold surface water was observed off the mouth of Juan de Fuca Strait and along the Washington coast, with the coldest, saltiest water off northern Washington (Figure 3). In June 2003, the freshest near-surface water was in a north-south band; offshore of the upwelling zone and not connected with the strait. Water properties of Juan de Fuca outflow undergo a strong fortnightly modulation [Hickey *et al.*, 1991] with surface salinity at the mouth ranging from 30.5–32.5. The time series of near-surface salinity from the mooring at the mouth of the strait (Figure 4) indicates that during this survey surface outflow from the strait was >31.5 , but in the ~ 5 d preceding the survey Juan de Fuca Strait outflow was ~ 31 , similar to the freshest water observed offshore. In contrast, the July 2005 survey (Figure 3), which was conducted when strait outflow was relatively fresh, clearly showed fresher water emanating from the strait and appearing to wrap around the more saline, upwelled water off northern Washington.

[19] A second region of low surface salinities (~ 31 – 31.2) was observed off the southern Washington coast during the July 2005 survey (Figure 3). This survey was preceded by a northward wind reversal of over a week in duration (Figure 2). During these typical summer storms, the Columbia River plume is directed northward onto the Washington Shelf often reaching as far north as La Push, WA [see Hickey *et al.*, 2005, Figure 1]. Such buoyant water on the inner shelf may delay the onset of upwelling for several days [Hickey *et al.*, 2005].

[20] In June 2003, two regions of elevated Chl *a* concentrations were observed: one offshore of Juan de Fuca strait, southeast of Barkley Sound, BC, and the other off the northern Washington coast (Figure 3). Low Chl *a* water, connected to the strait outflow, separated these two regions. Although Juan de Fuca outflow is nutrient-rich, it is generally low in phytoplankton biomass [Marchetti *et al.*, 2004]. Surface salinity data suggests the southern Chl *a* maximum was sustained by coastal upwelling whereas the northern maximum was more likely due to nutrient-rich outflow from the strait (see section 5.1). In July 2005, relatively high Chl *a* concentrations were again observed in the coastal upwelling region off Washington and in the lower salinity Juan de Fuca Strait water to the southeast of Barkley Sound.

3.2. Late Summer Surveys

[21] Three September surveys were conducted in a range of wind conditions: strong upwelling-favorable winds in 2003, downwelling-favorable winds in 2004, and a relaxation period of weak winds following sustained upwelling in

2005 (Figures 2 and 5). Winds were upwelling-favorable for several days prior to the beginning of the 2003 survey (1–6 September) and cold, saline surface water was present nearshore along the entire Washington coast (Figure 5). Relatively cold, saline water also extended in a broad region from the mouth of the strait across the shelf.

[22] The 2004 survey (10–16 September) was conducted during a period of moderate downwelling-favorable winds (Figure 2). Cold, saline surface water was again observed in a broad region on the northern Washington shelf (Figure 5). Fresher water was present nearshore along the Vancouver Island coast, indicative of water from the strait forming the Vancouver Island Coastal Current. Nearshore salinity values along most of the Washington coast were similar to offshore waters, consistent with coastal downwelling. However, fresher water was observed from Kalaloch Beach southward. This was the remnant of a plume from the Columbia River that had been slightly displaced offshore in the intermittent upwelling and downwelling that occurred immediately prior to these observations.

[23] The 2005 survey (15–22 September) occurred during a period of very weak winds (during the first 5 d of the survey wind magnitudes were <2 m s $^{-1}$, Figure 2). However, the survey was preceded by moderately strong southward winds resulting in relatively cold, saline, upwelled water along much of the Washington coast (Figure 5). The Juan de Fuca Eddy was evident during this survey as a distinct feature in the surface properties, with the fresh outflow from the strait wrapping around its northwest edge.

[24] In both late summer upwelling surveys (2003 and 2005), high Chl *a* concentrations were observed in the coastal upwelling region off Washington (Figure 5). In September 2003, a second maxima was also evident to the northwest of Barkley Sound. In 2004, maximum Chl *a* concentrations were observed along the northern Washington coast and in the Juan de Fuca Eddy region.

4. Variability in the Structure and Circulation of the Juan de Fuca Eddy

4.1. Spatial Structure

[25] The expression of the eddy in surface water properties has significant spatial variability (Figures 3 and 5). It is not always clearly evident (during early season surveys) or distinguishable from water on the northern Washington inner shelf (e.g., September, 2003). Closed contours are most common in surface salinity, as the saline, upwelled water in the eddy is distinct from the relatively fresh outflow from Juan de Fuca Strait. The structure becomes more eddy-like with increasing depth. For example, at 100 m all five surveys reveal a distinct feature on the southern Vancouver Island shelf with closed contours located approximately over the Tully Canyon (not shown). However, in the earliest of our five surveys (June 2003), the region of dense water does not extend west of the canyon at depths shallower than ~ 75 m, in contrast to the three September surveys (e.g., salinity at 50 m, Figure 6). The July 2005 middepth water properties do show a water mass consistent with the eddy near the Tully Canyon. However, it is more limited in spatial extent than in the later season data. In all three September surveys, a broad region of relatively saline water is evident at 50 m on the southwest Vancouver Island

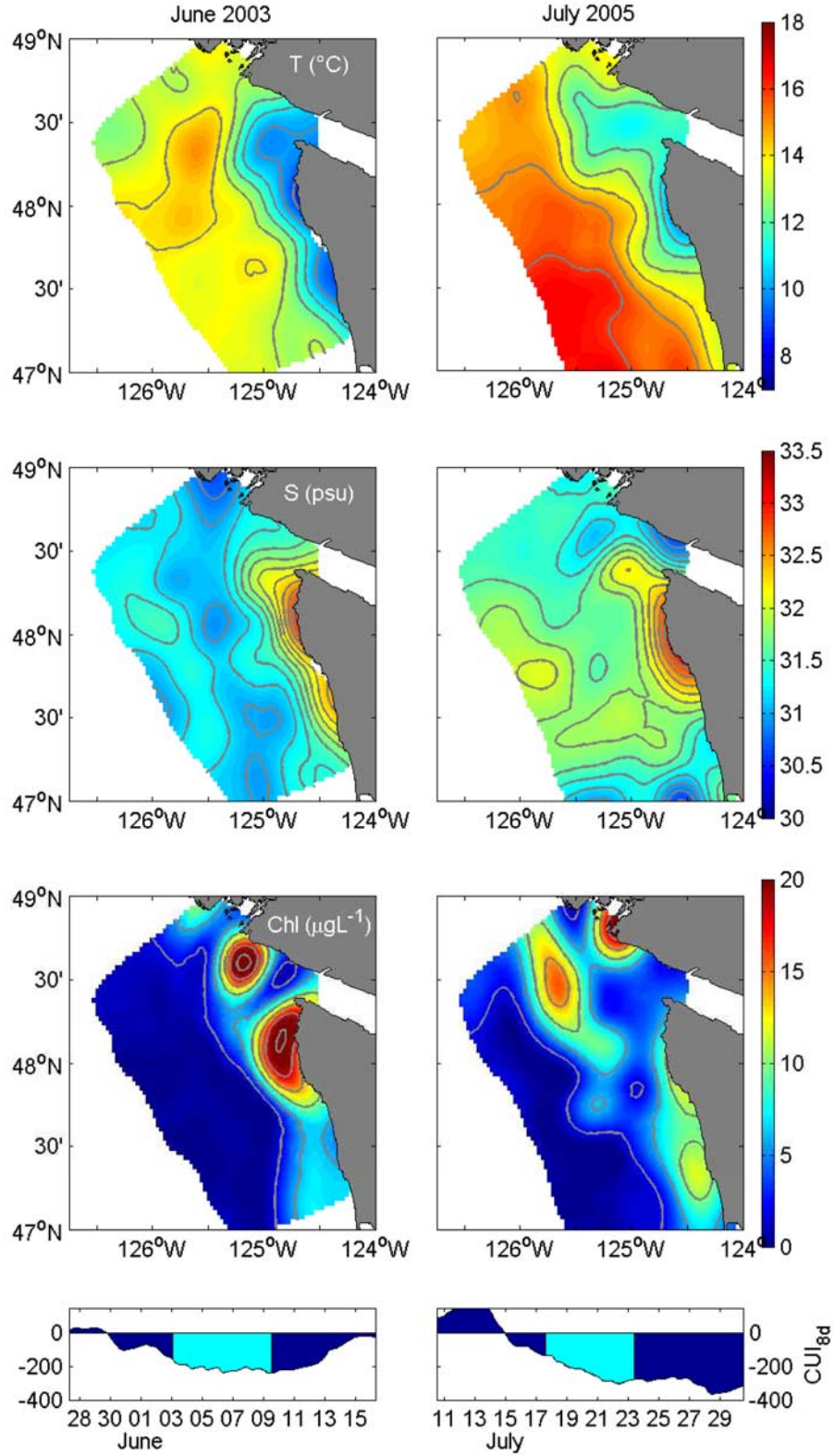


Figure 3. Surface temperature, salinity and Chl *a* concentrations measured during early summer surveys (June 2003 and July 2005). Contour intervals are 1°C , 0.2 psu , and $4 \mu\text{g Chl } a \text{ L}^{-1}$, respectively. The bottom shows the survey timing (light blue) in relation to an upwelling intensity index calculated from an 8-d weighted running mean of $\frac{\tau}{\rho f}$.

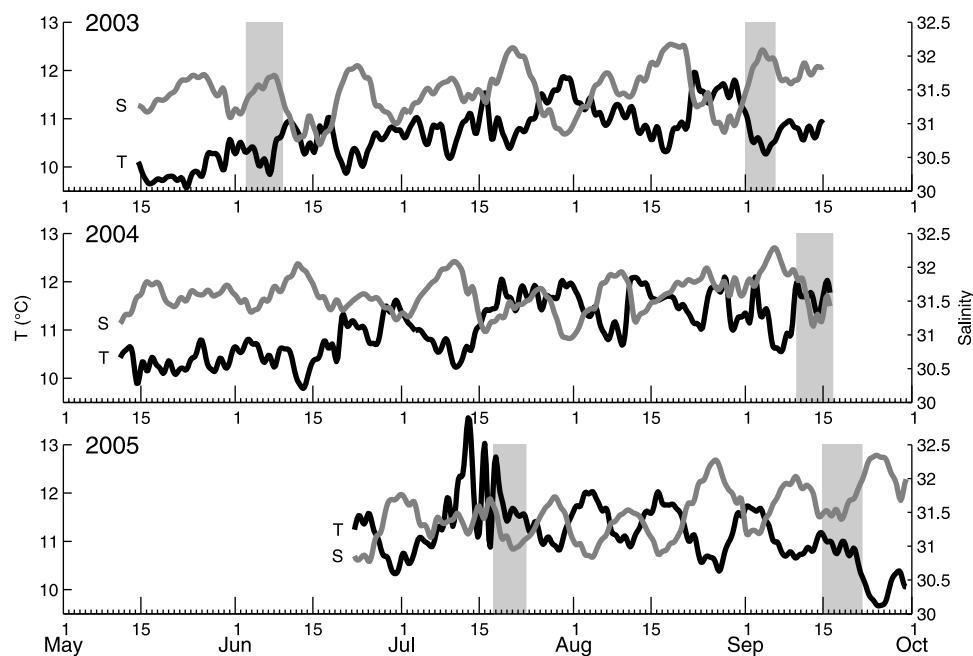


Figure 4. Time series of near-surface temperature and salinity measured by a moored sensor at the mouth of Juan de Fuca Strait during the summers of 2003–2005.

shelf approximately centered over the underlying Tully Canyon.

[26] In order to compare the depth-dependent spatial extent of the eddy among surveys we calculate a salinity anomaly. At each depth, this anomaly is defined as the difference between the measured salinity field and the mean for that depth. The eddy appears as a positive salinity anomaly on the northern Washington shelf (not shown, but identical in pattern to the salinity field, Figure 6). In the three actively upwelling cases (both early season surveys and September 2003), the maximum anomaly at 50 m and shallower is associated with strong upwelling on the northern Washington coast. However, in both the downwelling and relaxation from upwelling cases (September 2004 and 2005, respectively), at all depths the maximum anomaly is associated with the doming of California Undercurrent water at midshelf. As enhanced upwelling off Cape Flattery may be involved in eddy generation [Foreman *et al.*, 2008], we include this nearshore upwelling region in the subsequent eddy area calculation.

[27] At each depth, we approximate the eddy margin with the isohaline at which the salinity anomaly decreases by $1/e$ from its maximum value. For the 50 m case, shown in Figure 6, this is the region bounded by the heavy contour line. We then calculate the eddy area as the extent of the region bounded by this contour that falls within the shaded rectangle in Figure 6. The results of this calculation are expressed as an eddy “radius”, assuming a circular eddy. In actuality, the eddy shape is often more elliptical, as it may be elongated in the alongshore direction. The description as a “radius” is simply a more meaningful way to report results from our area calculation. These results indicate that the near-surface (upper 20 m) spatial extent of the eddy increases from early to late summer; radii range from ~ 15 km in June to 25–35 km in September (Figure 7). Below 100 m there is little evidence of this seasonal

increase and typical eddy radii are ~ 40 km. The eddy also increases in size with depth. In the early season data, the eddy radius at 100 m is approximately double its near-surface value. The later season results also show an increase in eddy radius with depth, however, the increase is more gradual at middepth.

4.2. Water Properties

[28] The salinity anomaly discussed above reflects the difference between the eddy and the mean regional conditions during that survey. However, there are also substantial differences in water properties within the eddy both intraseasonally and interannually. To illustrate variability in water properties in the core of the eddy, water property profiles from the station generally nearest the eddy center at depth (LAB04, within the Tully Canyon) are shown in Figure 8. The profile from earliest in the upwelling season (June 2003) is considerably fresher and warmer at middepth (50–100 m) than profiles from the other periods. However, T-S properties of water below 100 m are similar to the other profiles.

[29] In September 2004, water within the underlying canyon is almost 0.5°C warmer than in 2003 and 2005 (Figure 8). Time series data from the moored arrays also show warmer bottom water (mean increase of 0.3°C) at midshelf off Washington and at the mouth of the strait throughout the summer in 2004 (not shown). Profiles from within the eddy indicate that nitrate concentrations are reduced at all depths in 2004 relative to the other two years (Figure 8). For example, nitrate concentrations below 100 m are reduced by $\sim 5 \mu\text{M}$ in 2004. Water entering the Juan de Fuca Strait as part of the bottom estuarine flow is similarly reduced in nitrate.

[30] The observed variability of water properties within the Juan de Fuca Eddy can be quantified in terms of mixtures of source water types via water mass analyses.

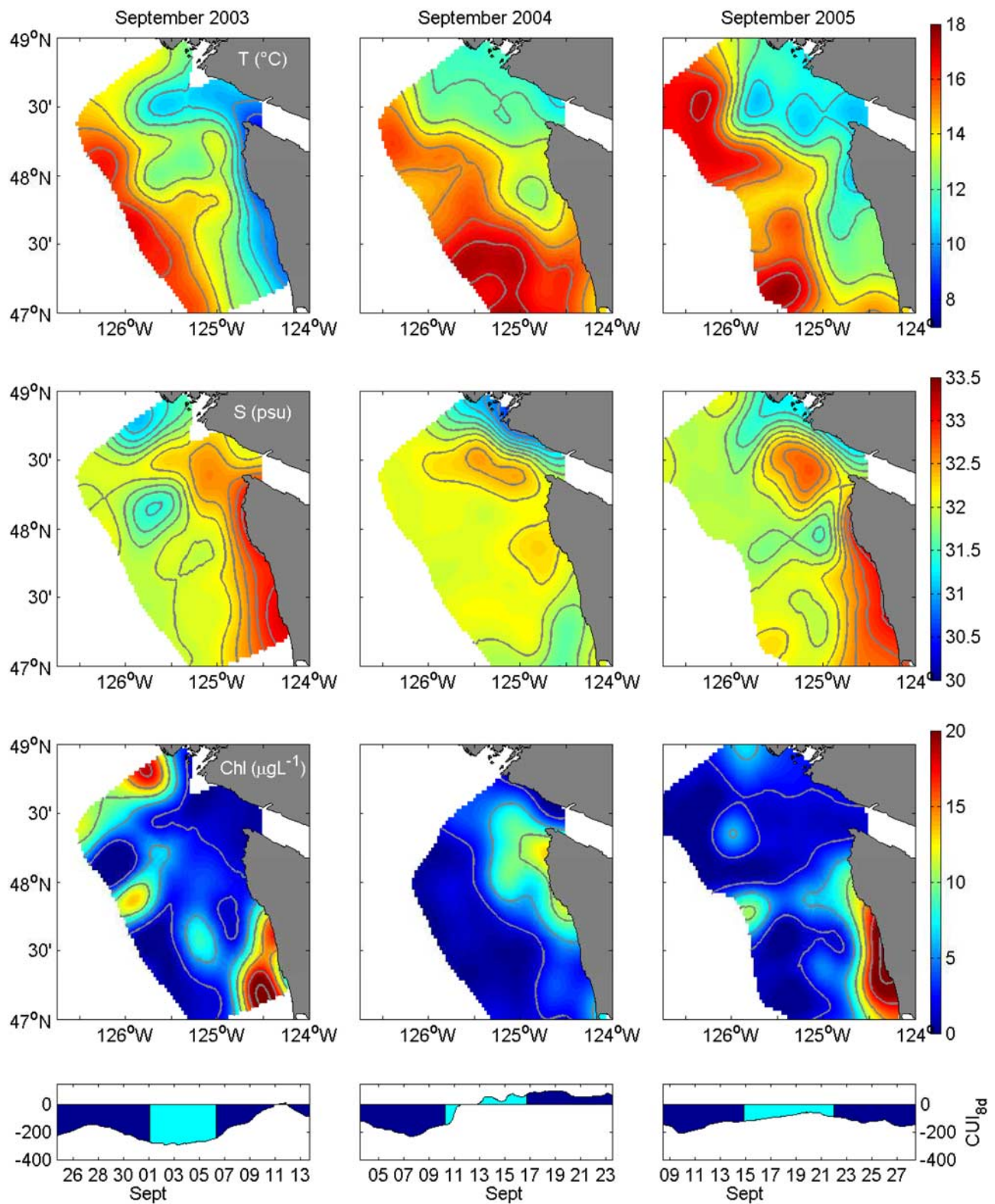


Figure 5. As in Figure 3 for late summer surveys (September 2003–2005).

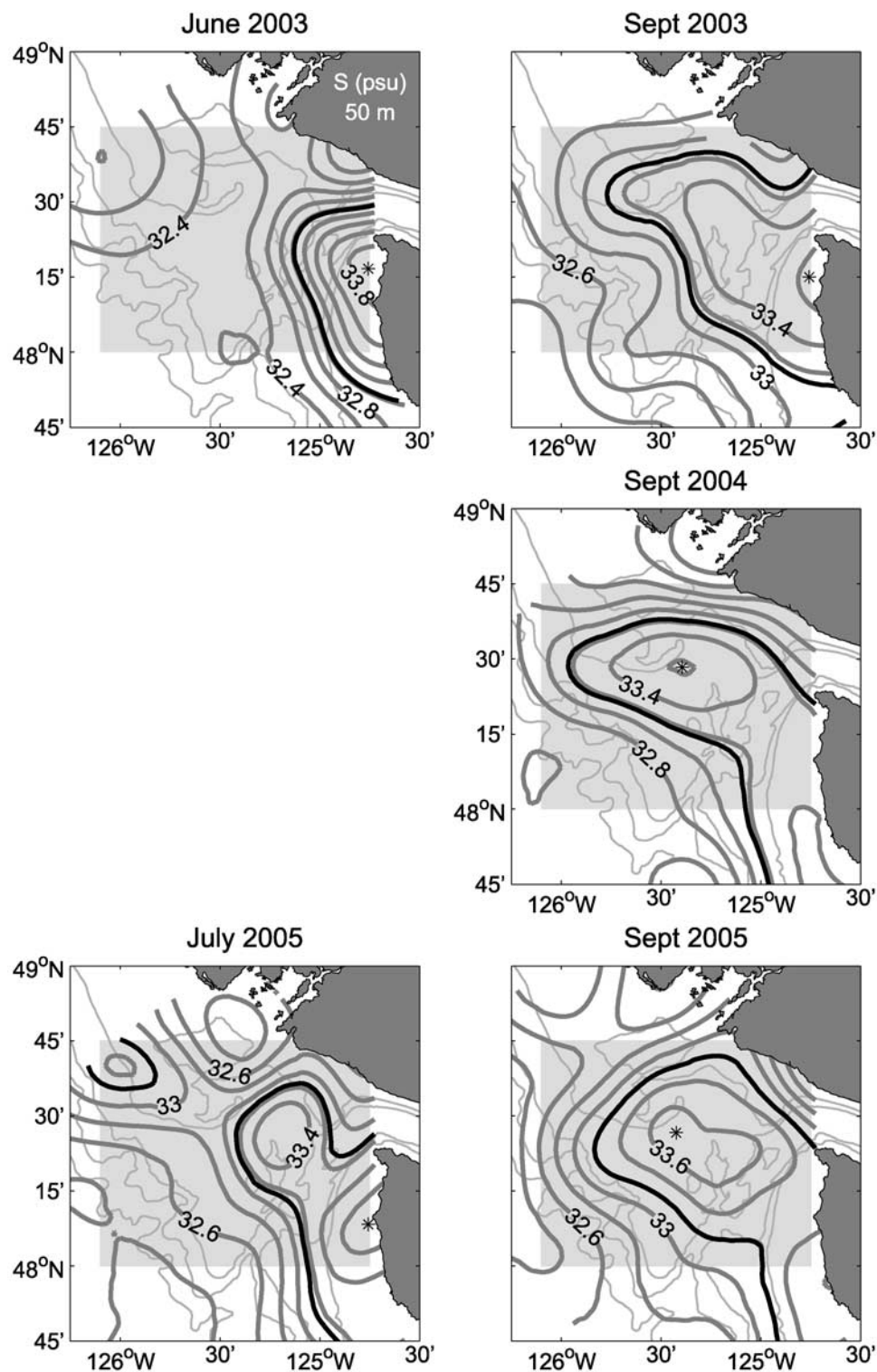


Figure 6. Salinity measured at 50 m during all five surveys. The locations of positive salinity anomaly maxima at this depth are marked with an asterisk (see text). Heavy contour marks the decrease in the salinity anomaly by one e -folding length scale.

Through a compilation of historical data from the northern California Current System and water mass analysis for the southern Vancouver Island shelf, *Mackas et al.* [1987] identified five source water types important to the region. These include: “California Undercurrent Core” ($\sigma_t = 26.6$,

200–300 m), “California Undercurrent Deep” ($\sigma_t = 27.0$, 450–500 m), “Offshore” ($\sigma_t = 25.3$, depth range 50–80 m), “Subarctic” ($\sigma_t = 26.6$, 125–175 m), and “Juan de Fuca” ($\sigma_t = 24.3$, ~30 m). In their analysis, the Juan de Fuca source water is actually a mixture of the fresh surface plume

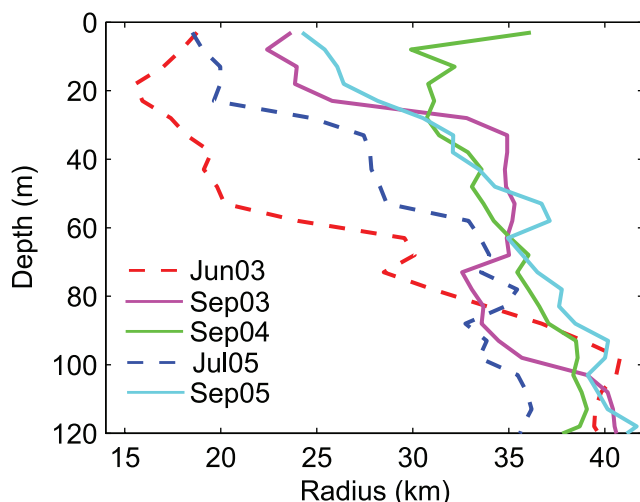


Figure 7. Eddy radius as a function of depth calculated from the decrease in the maximum salinity anomaly (see text for details).

of the Fraser River with the deep estuarine inflow (California Undercurrent water). However, it was sufficiently stable in its properties to be considered a primary source for shelf water analysis. We use these same five source water types in our present analysis. While the Columbia River can supply freshwater to the Washington shelf, northward directed plumes associated with summer storms rarely reach as far north as the Juan de Fuca Eddy. Since we restrict our water mass analysis to the northern Washington Shelf (and depths below 30 m), we do not include Columbia River water as an additional source in this analysis.

[31] Slope waters are primarily a mixture of three of the five source waters: the two California Undercurrent sources and the Offshore source water type. Characteristics for these three source waters are obtained by σ_t versus tracer regressions using all slope profiles from individual cruises (number of casts ranged from 47–85). Mean T-S source water definitions are shown in Figure 9 along with T-S curves computed from averaged slope profiles for each cruise. The T-S curves suggest an interannual warming trend in the slope waters penetrating to the depth of the upper California Undercurrent ($\sigma_t = 26.2$) relative to 2003. Considering only the September data, at 75 m depth, 2004 was $\sim 0.4^\circ\text{C}$ warmer than 2003, while 2005 was $\sim 0.8^\circ\text{C}$ warmer at the same depth.

[32] To define tracer characteristics for the Juan de Fuca source water, profiles within the strait are selected. However, due to a limited number of CTDs per cruise within Juan de Fuca Strait, and the strong fortnightly variability in water properties, tracer characteristics of this source water are defined by using tracer values measured over all five cruises (Figure 9). Mackas *et al.* [1987] found the Subarctic source water contributed only a small fraction ($<10\%$) to the water mass composition in their analysis. However, anomalous southward transport of Subarctic water has been recently observed [Freeland *et al.*, 2003]. Therefore we include this source water type using tracer characteristics taken from Mackas *et al.* [1987].

[33] Finally, in this analysis, all water mass properties are considered conservative. This assumption is clearly invalid in some regions, like the near surface where heating and biogeochemical processes may occur. In these regions, large residuals in the mass conservation constraint may occur, indicating a poor fit to the data. In our subsequent results, mass residuals are less than 0.1 except where indicated.

[34] Results from the water mass analysis within the eddy (station LAB04) are shown in Figure 10. In profiles at this station, the mass residual is less than 0.1 for all measurements deeper than 30 m. Not surprisingly, results indicate that the core of the eddy, at depths below 50 m, is composed primarily of California Undercurrent water. The presence of the eddy is associated with the doming of isopycnals over the southwest Vancouver Island shelf as deep California Undercurrent water is upwelled through the canyon system. The percentage of this source water can therefore be used as a measure of eddy development. Examining the early and late season profiles from 2003 illustrates the seasonal development of the eddy; in June the core of the eddy is only $\sim 35\%$ Undercurrent water at 50 m, compared to $\sim 85\%$ in September. Mackas *et al.* [1987] found the vertically averaged contribution from the Undercurrent source water to range from a winter low of $\sim 5\%$ to a summer high of $>70\%$ for a midshelf station slightly to the north of the LAB line. Performing the same calculation at our station yields a vertical average of $\sim 63\%$ in June and $\sim 83\%$ in September. Interestingly, July and September 2005 have very similar compositions of Undercurrent water (vertical averages are 81 and 85%, respectively), despite a delayed onset of persistent upwelling-favorable winds in this year [Hickey *et al.*, 2006; Schwing *et al.*, 2006].

[35] If we consider only the amount of California Undercurrent Deep water, that is, water originating from depths greater than 400 m, then the deep water within the eddy in September 2004 is composed of $<30\%$ of this source water

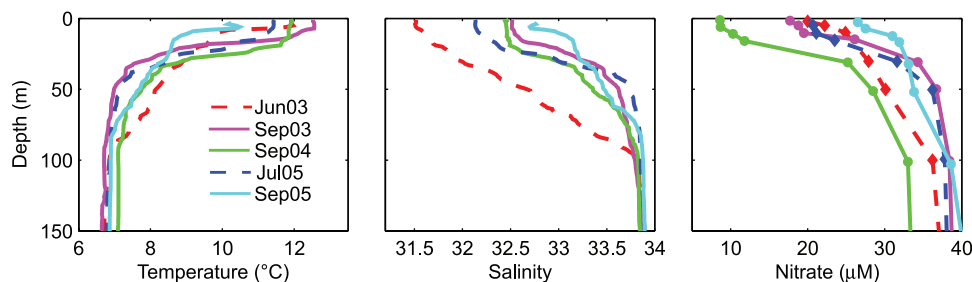


Figure 8. Vertical profiles of temperature, salinity and nitrate concentration measured at the station nearest to the eddy center at depth (LAB04).

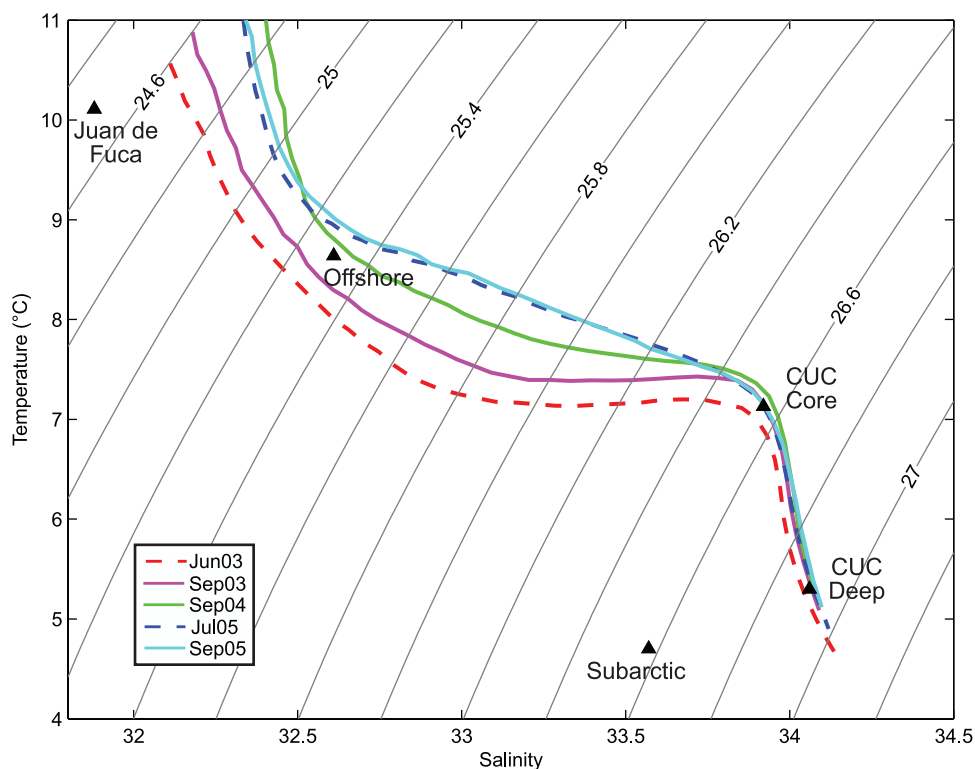


Figure 9. T-S diagram for continental slope water. Curves are computed for each cruise from the average of all CTD profiles (30–500 m) over the continental slope. Average source water definitions used in the water mass analysis are also shown (black triangles).

type, compared to 40–50% for the other time periods (Figure 10). The warmer deep shelf waters in 2004 (Figure 8) are likely a result of both the slight warming of the Undercurrent Core waters relative to the other years (Figure 9) and a reduction in this deep source water. Seasonal integrated wind stress in 2004 was low due to numerous reversals to northward wind over the course of the summer (Figure 2). It appears that the reduced seasonal mean upwelling intensity in 2004 resulted in upwelling of water from shallower depths and hence, warmer and slightly nutrient-depleted, deep water was present on the shelf.

[36] The relatively fresh water above ~100 m in the June 2003 profile (Figure 8) is identified by our model as increasing in its fractional composition of Juan de Fuca source water from <10% to ~100% at the surface (Figure 10). Surface waters offshore of the coastal upwelling

zone on the Washington shelf were much fresher in June 2003 than in the other surveys (Figure 3). We note that this survey was conducted when Fraser River outflow was nearest its seasonal maximum, which typically occurs in mid-June as a result of snowmelt. Although we neglect runoff from local rivers along the coast in our source water model, these flows generally peak during fall and winter and are an order of magnitude smaller than freshwater runoff driving the estuarine circulation in the Strait [Hickey *et al.*, 1991].

4.3. Circulation

[37] In this section, we use the diagnostic model described in section 2.5 to compare circulation in the eddy region among the five surveys (Figure 11). The model solution represents the circulation during the survey arising from the baroclinic pressure gradient. We do not explicitly

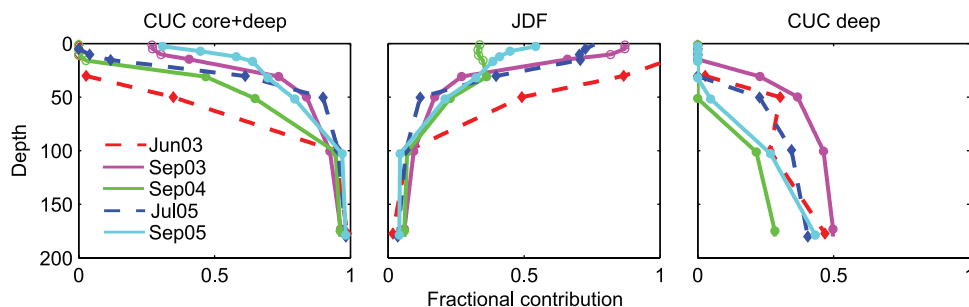


Figure 10. Depth profiles of percent composition of Juan de Fuca and California Undercurrent water (core + deep and deep only) in the eddy center. Marker types are shown as solid where a good fit to the data was achieved (<0.1 mass residual).

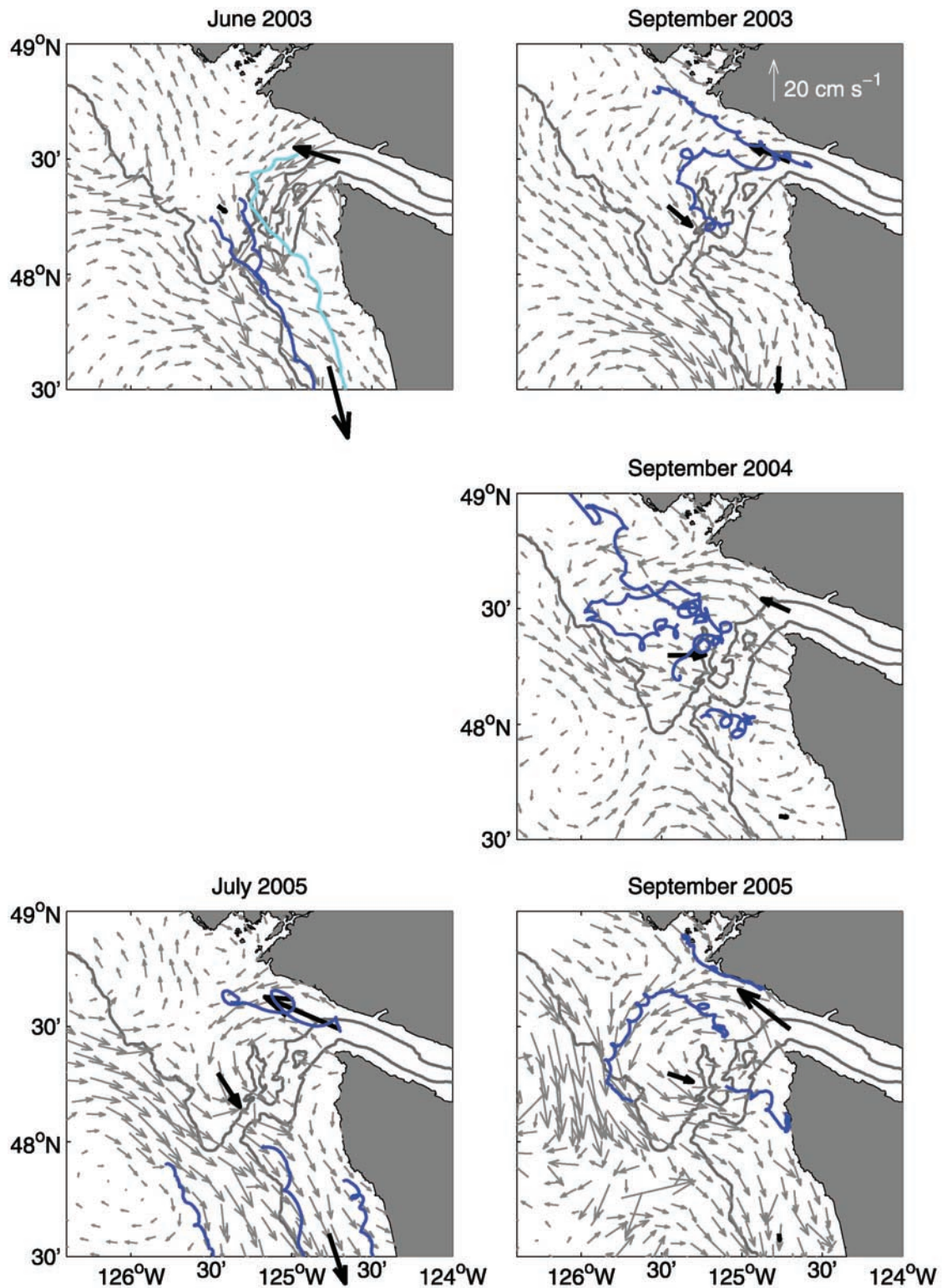


Figure 11. Diagnostic model surface circulation calculated from the survey data. Tracks from surface drifters are also shown; portions of tracks corresponding to the survey time period are colored dark blue. Average current vectors over the ~ 6 d survey periods were calculated from moored array data at 4 m and are shown in black.

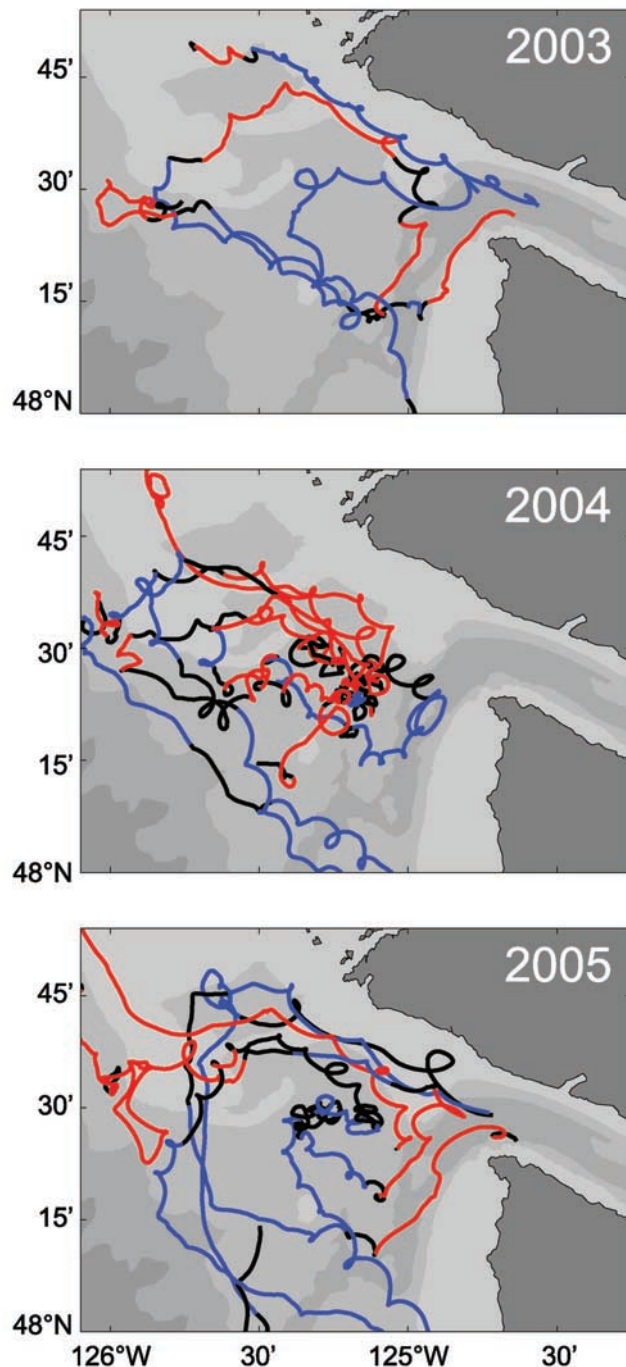


Figure 12. Tracks of surface drifters deployed in September 2003–2005. Portions of tracks are colored according to the direction of prevailing winds; northward (red), southward (blue) or weak ($<2 \text{ m s}^{-1}$, black).

include wind-forcing, however, the baroclinic solution alone may already incorporate part of the adjustment to the wind-driven event-scale sea surface slope. The lack of direct wind-forcing means that the model solution does not include the ageostrophic component of the currents in the surface Ekman layer. For comparison, averages over the survey periods of near-surface current vectors from the three moored arrays are superimposed. In addition, portions of

surface drifter tracks that were coincident with the timing of the surveys are shown (dark blue tracks, Figure 11).

[38] A southward shelf break current is evident in the model circulation for all survey periods with typical surface speeds of $10\text{--}15 \text{ cm s}^{-1}$. With the exception of the September 2004 survey period, currents on the Washington inner shelf are also generally southward, associated with the upwelling-favorable winds during these surveys. In September 2004, model results indicate a strong westward flow off the northern Washington coast. However, measured near-surface currents in this region are northward during downwelling wind conditions (Olympic Coast National Marine Sanctuary, unpublished data). This unrealistic offshore flow in the model is a result of the north-south density gradient in this region and the lack of direct wind-forcing. The chaotic offshore flow pattern to the south of the eddy in September 2005 also appears somewhat unrealistic and is likely the result of wavelike features in the hydrographic data.

[39] A cyclonic circulation pattern is evident westward of the mouth of the strait in both the early and late summer model solutions (Figure 11). This surface circulation is generally more evident than the expression of the eddy in surface salinity or temperature as it is primarily a result of the deep hydrographic structure. In the June 2003 survey, this cyclonic circulation occurs when a portion of the outflow from the strait turns southward around the relatively cold, saline water present off northern Washington. A surface drifter deployed at the mouth of the strait approximately one week after our June survey followed a similar pathway during a period of upwelling-favorable winds (light blue track, Figure 11). In results from the September surveys, the region of cyclonic circulation extends much further westward onto the shelf than earlier in the season and is consistent with the strongly domed isopycnals in this region (Figure 6). The eddy currents merge with the shelf break current to the west. In July 2005, the cyclonic circulation extends farther onto the shelf than in June 2003 but remains distinct from the shelf break current.

[40] Model circulation patterns calculated from the three September surveys also reflect the varying wind conditions under which they were conducted (Figure 11). In September 2003, during the period of sustained upwelling winds, the eddy is not a closed circulation pattern but rather a broad cyclonic flow off the mouth of the strait. During the northward wind period of September 2004, the circulation is compressed in the north/south direction and appears more closed and possibly more retentive. In both cases, typical surface current magnitudes within the eddy are similar, $\sim 10\text{--}15 \text{ cm s}^{-1}$. The eddy appears strongest and most circular during the relaxation period in 2005. In this case, the eastern side of the eddy is separated from Cape Flattery. Currents on the western edge of the eddy are much stronger than in other years, a response to the larger shelf edge gradient due to the warming of offshore waters in 2005 (Figure 9). In this case, typical surface speeds in the shelf-break current are $\sim 30 \text{ cm s}^{-1}$.

4.4. Eddy Retention/Escape

[41] As the model solution does not include the ageostrophic component of the currents in the surface Ekman layer, the eddy circulation (Figure 11) may appear much more retentive than actually occurs. To illustrate the effect

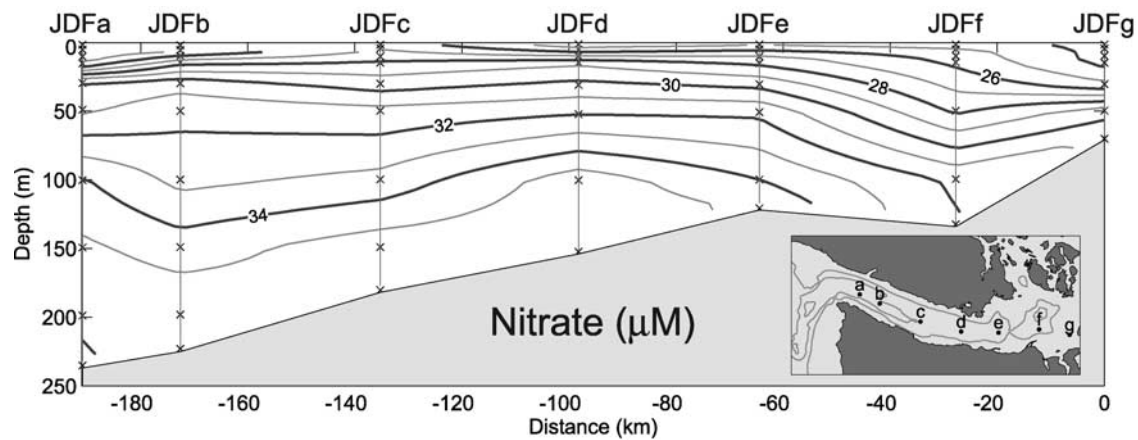


Figure 13. Vertical section of nitrate concentration measured in an along-axis Juan de Fuca Strait transect (18 September 2003). Station names are across the top of the section and geographically in the insert figure.

of the wind stress in modifying surface currents in the eddy, we use tracks from all surface drifters deployed during the three September cruises (Figure 12). Drifter tracks are colored corresponding to prevailing wind conditions (northward, southward or weak, $<2 \text{ m s}^{-1}$).

[42] Drifters generally move cyclonically unless exiting the region to the northwest (during northward wind periods) or southeast (during upwelling-favorable winds). Once drifters approach the southern edge of the eddy, their subsequent retention in the eddy is dependent on a northward wind at that time. Although previous observations on the Washington shelf have demonstrated that currents within the upwelling jet are strong enough to prevent north-south current reversals within the surface Ekman layer [MacFadyen *et al.*, 2005], no drifters escape the eddy to the south during periods of northward or downwelling-favorable winds. The combination of the wind-driven currents in the surface Ekman layer and the cyclonic geostrophic flow associated with the doming of deep isopycnals cause the eddy to be very retentive on the southern perimeter during periods of northward winds. Similarly, during southward or upwelling-favorable winds, the northern perimeter of the eddy is more retentive.

[43] Residence time of eddy surface water is estimated from the drifter tracks shown in Figure 12. We define residence time as the period from deployment to when a drifter exits the region shown, either to the north or south, or enters the strait (one drifter was recovered slightly south of the northern boundary). This estimate is highly variable as both wind conditions and deployment locations varied. One drifter released at the southern edge of the eddy reached the southern boundary in ~ 0.5 d. Another drifter released at approximately the same location moved north during a northward wind period and was retained in the eddy for ~ 32 d. The average retention time for all drifters was ~ 12 d. Retention times increased when winds were either weak or when frequent northward wind reversals occurred.

5. Regional Effects of the Juan de Fuca Eddy

5.1. Nutrient Enrichment of the Northern CCS

[44] The Juan de Fuca Eddy has been described as an “upwelling center”, allowing water to be raised from

deeper depths than in classical wind-driven upwelling [Freeland and Denman, 1982]. Upwelling in the eddy enriches the deep waters that flow into Juan de Fuca Strait as part of the estuarine circulation return flow. The penetration into the strait of this nutrient-rich water mass is evident in a vertical section of ambient nitrate concentration measured in September 2003 (Figure 13). At the mouth of the strait, nitrate concentrations below 100 m (the approximate depth of the division between inflow and outflow) are $>34 \mu\text{M}$. Similar concentrations are present in bottom water along the strait axis, reaching ~ 150 km east of the Strait entrance where strong mixing in shallow regions of high tidal currents mixes them upwards.

[45] The nutrient-rich waters observed in the euphotic zone of the southern Vancouver Island shelf are thought to derive primarily from this estuarine entrainment of deep water into the outflowing surface waters of the strait [Crawford and Dewey, 1989]. However, direct upwelling into the eddy may also be an important source of nutrients to the region. In this section, water mass analysis is used to distinguish these two sources and examine their relative importance. We also illustrate how variability in the circulation of the eddy and prevailing wind conditions can modify nutrient supply from Juan de Fuca Strait to the eddy region and the Washington coast.

[46] Surface nitrate distributions, measured over the three years of field studies, illustrate a reasonably comprehensive set of conditions: early season upwelling, and late-season upwelling, downwelling, and relaxation (Figures 14a and 14b, upper panels). In both June and September 2003 surveys, relatively high ambient nitrate concentrations are present along the entire Washington coast, a result of coastal upwelling. In June 2003, surface nitrate concentrations $>5 \mu\text{M}$ extend almost 50 km west off Cape Flattery, whereas later in the season (September) elevated nitrate concentrations extend much further seaward (~ 100 km offshore), consistent with the seasonal increase in offshore extent of the eddy. Similar nutrient distributions are evident in 2005 survey results, with nitrate concentrations $>5 \mu\text{M}$ extending ~ 60 km offshore in July and ~ 100 km offshore in September. In September 2004, during downwelling-favorable wind conditions, moderate levels of surface nitrate

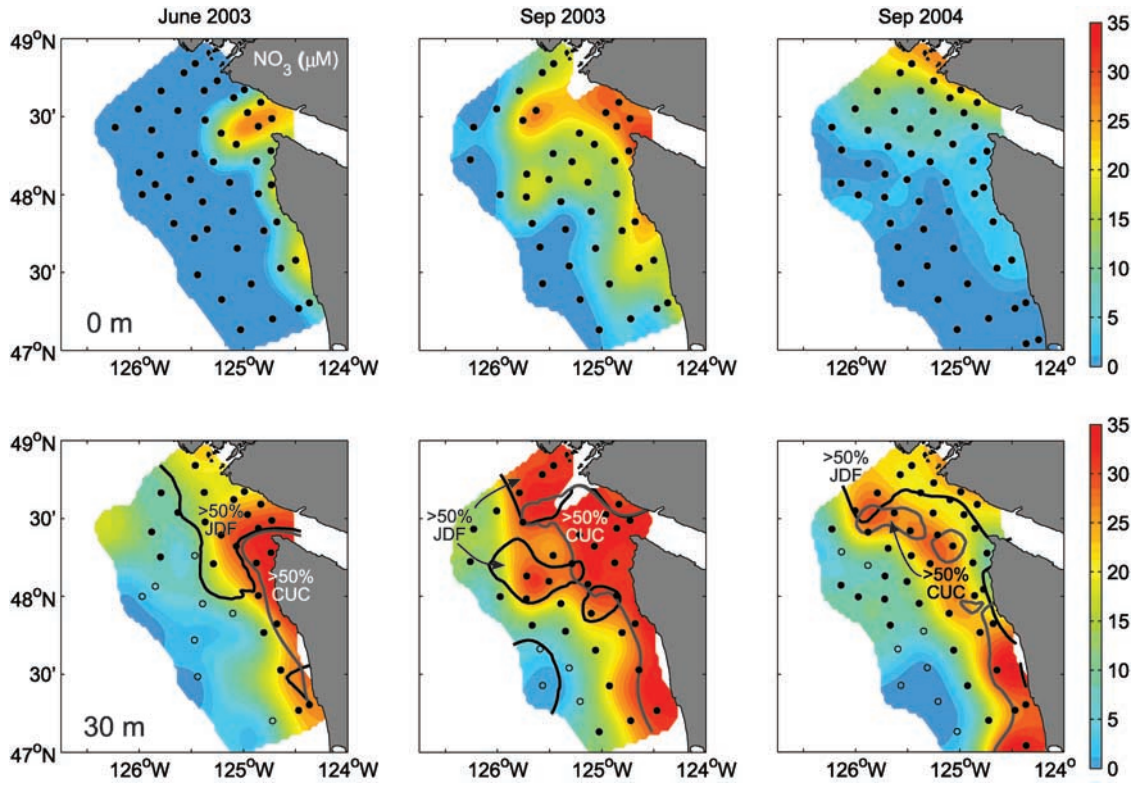


Figure 14a. Ambient nitrate concentration during the first three surveys (June/September 2003 and September 2004) at 0 m (top) and 30 m (bottom). Bottom panels include contours from the water mass analysis indicating contributions of $\geq 50\%$ California Undercurrent (core plus deep; heavy gray line) and $\geq 50\%$ Juan de Fuca source waters (heavy black line).

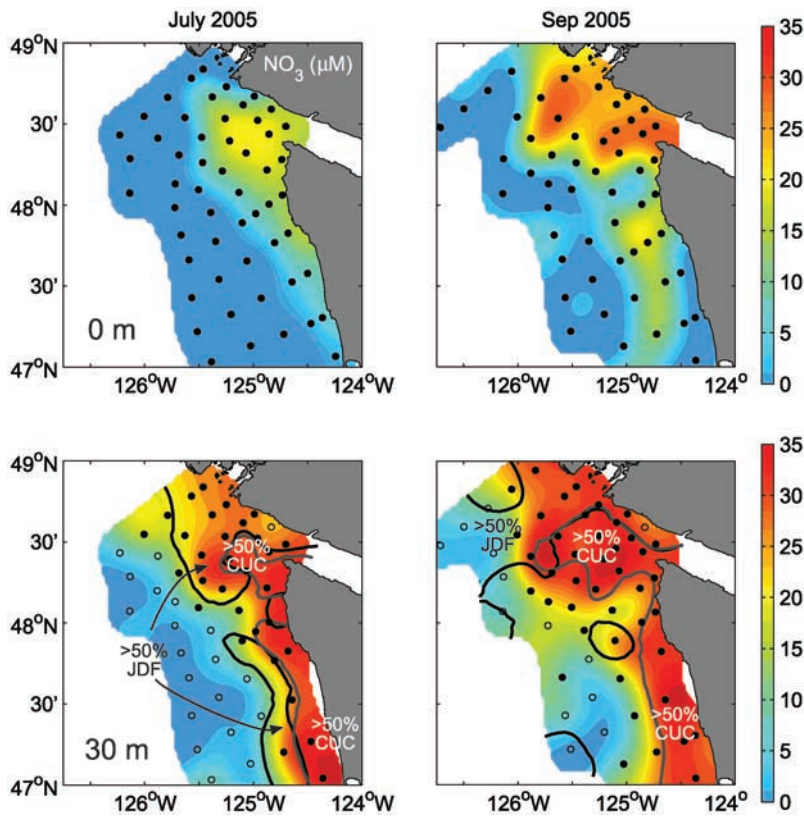


Figure 14b. As in Figure 14a for July/September 2005 surveys.

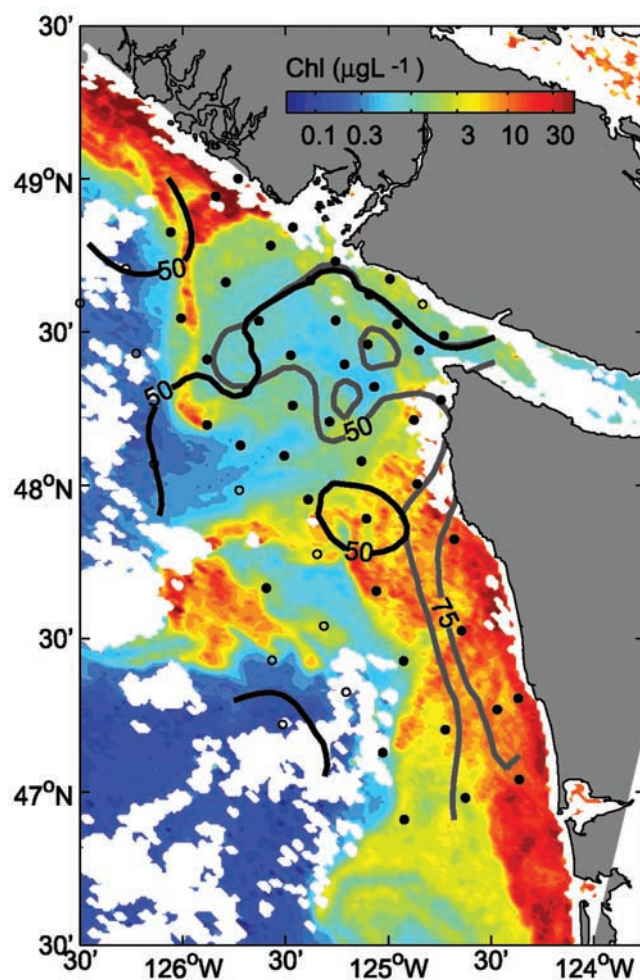


Figure 15. SeaWiFS Chl *a* measured 20 September 2005. Contours from water mass analysis of $\geq 50\%$ California Undercurrent (core + deep) and $\geq 50\%$ Juan de Fuca source waters are also shown.

($\sim 10 \mu\text{M}$) are still found in the eddy region, in contrast to the Washington coast where ambient nitrate ranges from undetectable ($< 0.10 \mu\text{M}$) in the south to a maximum of $\sim 4.5 \mu\text{M}$ in the north.

[47] To differentiate the source waters contributing to the elevated nutrient concentrations, the contours from the water mass composition analysis are plotted on nitrate at 30 m, the shallowest depth at which a good fit to the data is generally achieved (Figures 14a and 14b, lower panels). The contours delineate areas that are composed of $\geq 50\%$ Juan de Fuca source water or $\geq 50\%$ California Undercurrent source water (both Core and Deep).

[48] In all surveys, both Juan de Fuca and California Undercurrent water contribute to the broad regions of high nitrate observed. In both early and late-season surveys, the Juan de Fuca Strait source water is advected cyclonically around the denser California Undercurrent water, resulting in the wider offshore extent of high ambient nitrate. Later in the season, when the eddy is more developed, this water is transported much further seaward. During downwelling conditions (September 2004), the nutrient-rich Juan de Fuca

effluent is largely confined to a narrow-band nearshore off Vancouver Island.

[49] At this depth (30 m) and below, the core of the eddy is comprised mainly of California Undercurrent water (Figures 10, 14a and 14b). In the three September surveys, the highest concentrations of nitrate at 30 m are in the eddy core, aligned with the maximum composition of California Undercurrent water. In 2004, ambient nitrate concentrations are reduced relative to the other years (Figure 8). In June 2003, highest nitrate concentrations at this depth are on the inner Washington shelf, associated with wind-driven coastal upwelling of California Undercurrent water (Figure 14a).

[50] We conclude that in later summer, when the eddy is fully developed, direct upwelling of nutrient-rich water is the dominant nutrient supply mechanism to the eddy interior, to depths at least as shallow as the base of the mixed-layer. Earlier in the season, when the eddy is less developed and Fraser river outflow is at its peak, the Juan de Fuca source water may dominate nutrient supply to the eddy region. The two sources together contribute to making the northern extent of the California Current extremely nutrient-rich. In both cases, macronutrients originate from the California Undercurrent, but both the timescales of delivery and the pathways through which they reach the euphotic zone are very different.

5.2. Phytoplankton Biomass Distributions

[51] Our survey results indicate that areas of high phytoplankton biomass (as Chl *a*) in the eddy region are generally confined to its margins (Figures 3 and 5). In several of the surveys (September 2003, July and September 2005), Chl *a* maxima are evident in the fresher waters on the western and northern edges of the eddy. Previous studies identified a persistent region of high planktonic biomass located over the outer edge of the continental shelf [Denman *et al.*, 1981]. Satellite-derived estimates of Chl *a* concentrations for the region also consistently showed relatively higher concentrations over the Vancouver Island slope than the Washington slope [Sackmann *et al.*, 2004]. Denman *et al.* [1981] indicated that the band of elevated phytoplankton biomass observed in their study was supported by nutrients mixed up into the euphotic zone from the bottom waters of the bank. Our results demonstrate an additional supply mechanism; later in the summer, the presence of the eddy can facilitate transport of nutrient-rich Juan de Fuca strait water as far seaward as the Vancouver Island slope (Figure 14a and 14b).

[52] Interestingly, the nutrient-replete eddy center is often devoid of phytoplankton. Seasonal mean satellite fluorescence data show that a strong, broad Chl *a* maximum does occur in the eddy region in the spring, whereas later in the season, maxima are typically confined to the offshore edge [Edwards and Hickey, 2005]. A striking example is evident in a satellite image from 20 September 2005, near the end of our survey period for that year (Figure 15). Chl *a* concentrations are near the minimum detection limits throughout much of the eddy, with elevated levels in a tendril on the western edge. Chl *a* concentrations are also high to the north of the eddy and on the Washington shelf. Survey results from the corresponding time period indicate that the core of the eddy was replete with nitrate, with surface concentrations exceeding $25 \mu\text{M}$ (Figure 14b; survey lines within the

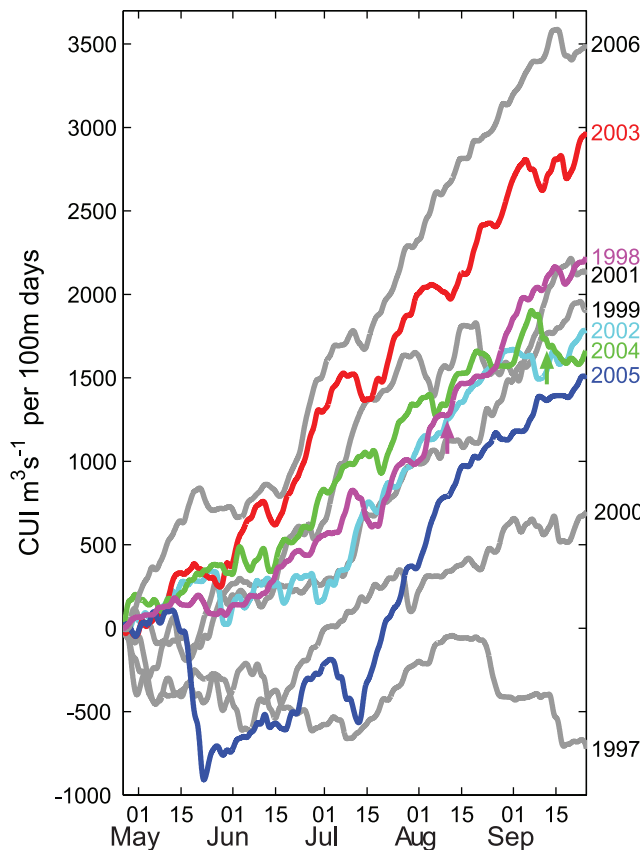


Figure 16. Seasonal upwelling intensity index (as in Figure 2) for the summers of 1997–2006. Vertical arrows mark periods mentioned in text when concentrations of *Pseudo-nitzschia* and toxin were measured in the eddy.

eddy were sampled 19–21 September). Water mass analysis (at 30 m) indicates that the core of the eddy at this time was comprised largely of California Undercurrent source water. These results suggest that the pathways through which macronutrient-rich water reaches the euphotic zone may be very important to subsequent phytoplankton growth. Early in the season, when Juan de Fuca water is the primary source water in the eddy region, the broader, larger Chl *a* maximum is observed.

[53] In contrast to the other periods, a broad region of elevated Chl *a* was observed throughout the eddy region during the September 2004 survey (Figure 5). During this time, the highest concentrations of *Pseudo-nitzschia* cells and domoic acid ever observed in this region were also measured in the Juan de Fuca Eddy [Trainer et al., 2008]. However, even when present at extremely high densities ($>10^6$ cells L^{-1}), *Pseudo-nitzschia* spp. never dominated the phytoplankton community biomass [Trainer et al., 2008].

5.3. Development and Export of Toxic *Pseudo-nitzschia* Blooms

[54] The spatial extent and magnitude of the September 2004 toxic event make it an ideal case study to examine differences in the structure or circulation of the eddy that contribute to the development of large blooms of *Pseudo-nitzschia* in this region. The summer of 2004 was previously characterized as having reduced seasonal upwelling inten-

sity relative to 2003. However, when compared to time series of cumulative upwelling indices for the past ten years, 2004 is close to a mean seasonal index (Figure 16). Such years tend to have periods of moderate upwelling-favorable winds interrupted by frequent reversals to northward winds. Under these conditions the Juan de Fuca Eddy appears to be more retentive to surface waters. For instance, the longest residence time for a surface drifter in the eddy (~ 32 d) was observed in September 2004 (average retention time is ~ 12 d, section 4.4). As previously discussed, nutrient concentrations within the eddy were reduced in 2004 relative to the other 2 years. However, ambient nitrate concentrations were still moderate ($5\text{--}10\text{ }\mu\text{M}$) and, based on laboratory studies, sufficient to support near maximal nitrate utilization rates by *Pseudo-nitzschia* cultures [Auro, 2007; Cochlan et al., 2008]. The resident diatoms may have been physically retained for some time in the eddy while being continually resupplied with nutrients for their sustained growth, with nutrients originating either from the strait or through mixing from below (note the elevated nitrate at 30 m, Figure 14a).

[55] Toxigenic diatoms present in the Juan de Fuca Eddy pose a serious problem for Washington State benthic fisheries only if they are advected to the coast. This requires a period of sustained upwelling, during which time the currents in the southern margin of the eddy are directed southeastward, allowing particles to escape the eddy (Figure 12), followed by a storm with associated onshore advection [MacFadyen et al., 2005]. Fortunately, this did not occur in the late summer of 2004, when unprecedented concentrations of toxic phytoplankton cells were present in the eddy. Local winds were northward through much of late-August and early September (Figure 2) and surface drifters (particles) were mostly retained in the eddy (Figure 12). When drifters did ultimately escape the eddy to the south in late September, they remained offshore during a ~ 10 d period of reasonably steady southward winds.

[56] In the past 10 years, large coast-wide toxications of razor clams have occurred twice, in mid-September 1998 and again in 2002. These years were also characterized by moderate seasonal upwelling intensity with frequent northward wind reversals (Figure 16). The cumulative upwelling indices for the 1998 and 2004 summers are very similar, until approximately the beginning of September. In 1998, *Pseudo-nitzschia* cells and domoic acid were measured in the southern portion of the eddy in mid-August [Trainer et al., 2002]. Following this, a sustained upwelling period occurred, likely allowing toxic cells to escape the eddy and be advected southward onto the Washington shelf.

6. Summary

[57] In this paper, we present data from three years of field studies conducted in the Juan de Fuca Eddy region. Although previous studies have characterized the structure and circulation associated with the eddy, multidisciplinary data obtained on five regional surveys allow us to examine variability in this mesoscale feature, and to illustrate the impact of this variability on macronutrient supply, the distribution of phytoplankton biomass, and toxigenic *Pseudo-nitzschia* blooms in the northern California Current System. Our survey results demonstrate that the eddy increases in spatial extent from early to late summer as

California Undercurrent water is upwelled onto the shelf, presumably through the underlying canyons. The percentage of Undercurrent water on the shelf increases throughout the summer, accounting for ~63% of the water column at midshelf in June and >80% later in the season. This water mass also penetrates to increasingly shallow depths as the season progresses, ultimately reaching depths as shallow as the base of the mixed layer. The near-surface eddy radius, determined by the extent of a positive salinity anomaly, increases from early to late summer: typical radii are ~15–20 km in June/July and 25–35 km in September.

[58] During the upwelling season, approximately late-April to September, seasonal-mean currents offshore of Juan de Fuca Strait are primarily determined by the presence of the eddy. The regional circulation is modified by changes in the deep structure of the eddy, such as occurs during its seasonal growth, and by prevailing wind conditions. During typical southward wind conditions, the combination of the cyclonic geostrophic flow and the wind-driven currents in the surface Ekman layer cause the eddy to be “leaky” on its southern perimeter. However, during periods of weak winds, or when frequent northward wind reversals occur, the surface circulation in the eddy becomes more retentive.

[59] The presence of the eddy facilitates large inputs of dissolved inorganic nutrients to the area and thus has a major impact on regional nutrient distributions. Nutrients are supplied to the region through two primary mechanisms: direct upwelling of California Undercurrent water onto the shelf, and enhanced cross-shelf advection of Juan de Fuca Strait outflow. The penetration of Undercurrent source water to increasingly shallow depths throughout the season results in elevated nutrient concentrations over a large portion of the northern Washington shelf. The eddy also transports Juan de Fuca water across-shelf by advecting it cyclonically around the eddy margin, resulting in elevated nutrient concentrations ~100 km offshore. Unlike the coastal upwelling zone, this region maintains moderate levels of near-surface nutrients even during frequent reversals to northward winds.

[60] These two mechanisms, direct upwelling of California Undercurrent water and cross-shelf advection of Juan de Fuca water, together contribute to making the northern extent of the California Current extremely nutrient-rich. However, our late summer surveys indicate that areas of high phytoplankton biomass are generally confined to the eddy margins, and the nutrient-replete center is often devoid of phytoplankton. Finally, the Juan de Fuca Eddy has been implicated as an initiation region for toxigenic *Pseudo-nitzschia* blooms which impact the Washington coast. The massive toxic bloom observed during the September 2004 survey occurred during a year with moderate, cumulative seasonal upwelling wind intensity due to frequent northward wind reversals. Similar conditions occurred in the summers of 1998 and 2002. Early fall cancellation of recreational harvesting of razor clams occurred during both these years. Under these conditions, the Juan de Fuca Eddy is extremely retentive to surface particles; a surface drifter deployed in the eddy in September 2004 remained in the area for over a month. Blooms of harmful or benign algae may be retained for long periods in the region while being periodically resupplied with nutrients. Ultimately, the exact

sequence of wind-conditions in the late summer determines whether toxic blooms of phytoplankton within the eddy pose a problem for Washington State benthic fisheries.

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