JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 114, C00B03, doi:10.1029/2008JC004907, 2009

Three interacting freshwater plumes in the northern California Current System

B. Hickey,[1] R. McCabe,[2] S. Geier,[1] E. Dever,[3] and N. Kachel[1]

Received 9 May 2008; revised 3 October 2008; accepted 24 October 2008; published 8 January 2009.

[1] The northern California Current System is impacted by two primary freshwater sources: the Strait of Juan de Fuca and the Columbia River. The Columbia is frequently bidirectional in summer, with branches both north and south of the river mouth simultaneously. We describe the interaction of these two warm Columbia plumes with each other and with the colder plume originating from the strait. The interactions occurred when a period of strong downwelling-favorable winds and high Columbia River discharge was followed by persistent and strong upwelling-favorable winds. The northward plume that developed under the downwelling winds extended over 200 km along the coast to the Strait of Juan de Fuca and into the strait. The plume subsequently wrapped around Juan de Fuca Strait water in the counterclockwise seasonal eddy just offshore of the strait. Inspection for similar wind and outflow conditions (>0.15 N m^{-2} and 10^4 m^3 s^{-1}, respectively) suggest that these events might have occurred in roughly half the years since 1994. Surface drifters deployed in the Columbia plume near its origin tracked this plume water northward along the coast, then reversed direction at the onset of upwelling-favorable winds, tracking plume water southward past the river mouth once again. "Recent" (∼1–2 day old) and "Aged" (>14 day old) plume water folded around the newly emerging southwest tending Columbia plume, forming a distinctive "sock" shaped plume. This plume was a mixture of ∼10% "New" (<1 day old) water and ∼90% Recent and Aged water from prior north tending plumes.

Citation: Hickey, B., R. McCabe, S. Geier, E. Dever, and N. Kachel (2009), Three interacting freshwater plumes in the northern California Current System, *J. Geophys. Res.*, *114*, C00B03, doi:10.1029/2008JC004907.

1. Introduction

[2] The California Current System (CCS) north of the Columbia River mouth is extremely complex: currents respond to several point sources of buoyancy, local and remote wind forcing and bottom topography that includes both offshore banks and a number of submarine canyons. The primary sources of freshwater in summer are the Fraser River, whose water enters the Strait of Juan de Fuca, and the Columbia River (Figure 1). Freshwater flux from the other coastal estuaries, Grays Harbor and Willapa Bay (Figure 1), are typically two orders of magnitude less than that from the other freshwater sources [*Hickey and Banas*, 2003].

[3] Historically the outflow from the Columbia River was viewed as a freshwater plume oriented southwest offshore of the Oregon shelf in summer and north or northwest over the Washington shelf in winter [*Barnes et al.*, 1972; *Hickey et al.*, 1998]. For this reason, most modeling studies for the Oregon coast have their northern boundary south of the Columbia, or extend farther north but do not include the Columbia [e.g., *Gan and Allen*, 2005]. Modeling studies on the southern British Columbia/northern Washington coast have also ignored the influence of the Columbia plume [*Masson and Cummins*, 1999; *Foreman et al.*, 2008]. However, recent data-based results show that the Columbia plume is frequently present up to 160 km north of the river mouth from spring to fall, even during periods of strong upwelling-favorable wind stress [*Hickey et al.*, 2005]. The plume is frequently bidirectional, with branches simultaneously north and south of the river mouth [*Hickey et al.*, 2005]. The freshwater plume that emerges from the Strait of Juan de Fuca has generally been thought to transport the majority of its water along the Vancouver Island coast [*Thomson et al.*, 1989; *Hickey et al.*, 1991]. Consequently models of the Washington shelf have placed their northern boundary south of the complex strait region [*MacCready et al.*, 2008]. However, recent drifter studies have shown clearly that in spring and summer a large portion of water from the strait moves southeastward and then southward along the Washington shelf [*MacFadyen et al.*, 2005, 2008].

[4] This paper uses data from satellite sensors, moored arrays, surface drifters and CTD surveys to demonstrate that the three freshwater plumes, Juan de Fuca, north Columbia and southwest Columbia, interact strongly with each other

[1]School of Oceanography, University of Washington, Seattle, Washington, USA.
[2]Department of Aviation, University of New South Wales, Sydney, New South Wales, Australia.
[3]College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon, USA.

0148-0227/09/2008JC004907$09.00

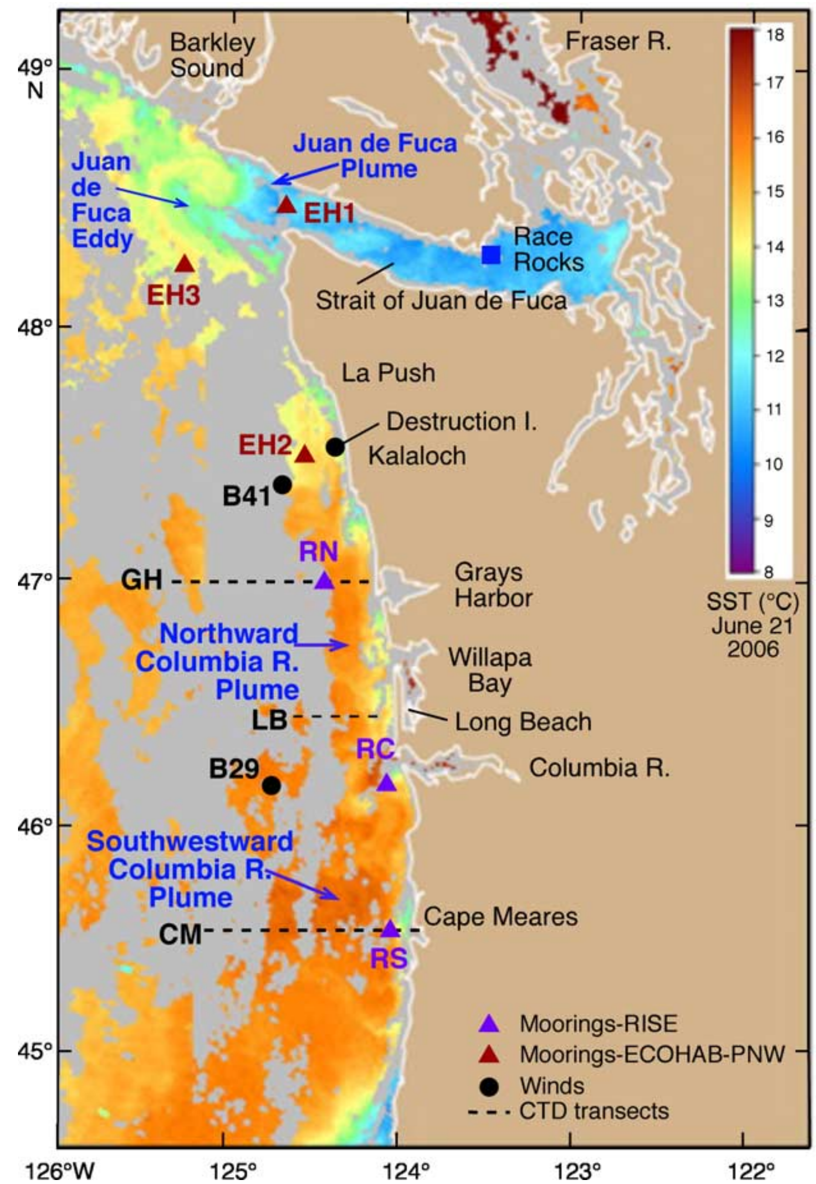

Figure 1. Satellite-derived sea surface temperature on 21 June 2006, illustrating the three buoyant plumes addressed in this paper: Juan de Fuca, northward Columbia River and south or southwestward Columbia River. Significant coastal features, moored sensor arrays, NDBC wind buoys and CTD sampling sections are also shown. The Columbia River divides the U.S. west coast between Washington in the north and Oregon in the south. Vancouver Island (British Columbia, Canada) is the landmass north of the Strait.

and jointly determine the distribution of freshwater and nutrients in the northern CCS both north and south of the Columbia River. New data used in the analysis are described in the next section. Results are given in section 3, focusing on development of a north tending plume from the Columbia; interaction of this plume with the plume from the Strait of Juan de Fuca; development of a "New" (<1 day old) southwest tending plume from the Columbia; and merging of "Recent" (~1–2 day old) and "Aged" (>14 day old) Columbia water in the north tending plume with the newly forming southwest tending Columbia plume. Potential and observed impacts of these merging buoyant plumes are summarized in the last section.

2. Data and Analysis Methods

[5] Hydrographic data were obtained on RISE (River Influences on Shelf Ecosystems) cruises on the R/V *Wecoma.* The data were collected using a Sea-Bird Electronics SBE 911*plus* Conductivity (C), Temperature (T), and Depth (D) system with dual temperature and conductivity sensors. Data were recorded on downcasts, with a descent rate of 30 m min^{-1} in the top and bottom 100 m of each cast, and

up to 50 m min^{-1} over the remainder of each cast. The data were averaged into 1 m bins. Quality control consisted of removing spikes that created σ_t inversions >0.02 kg m^{-1}. Conductivity values causing such inversions were removed and the resulting gaps (if less than 2–3 m) were filled using linear interpolation. Data within 3 m of the surface were often lost or contaminated due to the wave-induced or underway motion of a large vessel. Therefore near surface data were replaced with data taken from an SBE 45 located at a depth of 2 m near the bow of the ship. To provide salinity calibrations, water samples were collected via a rosette system at approximately every third station for analysis by an autosalinometer onboard the R/V *Wecoma.* After calibration the salinity accuracy was better than 0.01 psu (practical salinity units). After the temperature and conductivity profiles were de-spiked, salinities and densities were recalculated.

[6] In survey maps, CTD data were supplemented with salinity data from the ship's underway system consisting of an SBE 3 measuring temperature and an SBE 4 measuring conductivity. Both sensors were located in the ship's wet lab, with the seawater intake at ~4 m at mid ship.

[7] Moored sensors were deployed as components of two regional programs: Ecology and Oceanography of Harmful Algal Blooms Pacific Northwest (ECOHAB PNW) and RISE. The ECOHAB PNW moorings were located on the northern shelf, inside the Strait of Juan de Fuca and in the eddy offshore of the Strait. RISE moorings were deployed on the shelves north and south of the Columbia River mouth and offshore of the mouth (see locations in Figure 1). ECOHAB PNW moorings (EH1, 2, 3) were surface moorings, suspended from toroidal buoys. Temperature and conductivity were measured with a Sea-Bird Electronics SBE 16*plus* at 4 m and an SBE 37 at 15 m. Current meters were all vector measuring, with an InterOcean S4 mounted at 3 m and a downward looking Teledyne RD Instruments 300 kHz Workhorse Sentinel Acoustic Doppler Profiler (ADCP), with the first good data typically at ~10 m. Sampling rates varied on the instruments but were typically 30 min or less. RISE moorings (RN, RC and RS) were also surface moorings supported by toroidal buoys. Sea-Bird Electronics SBE 16*plus* sensors were located within the buoy well at ~1 m, and at 5 and 20 m. A downward looking Teledyne RD Instruments 300 kHz Workhorse ADCP was also located within the buoy well. The first good velocity data were obtained near 3 m. 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 to produce "subtidal" time series.

[8] Lagrangian satellite-tracked drifters were deployed during RISE to track emerging freshwater plumes and to provide surface velocity measurements. Drifter models included Brightwaters Instrument Co. models 104A (onboard logging, with C and T sensors) and 115 (no onboard logging, T only). These drifter models are designed according to the Davis/CODE configuration to accurately track the top 1 m of the water column [*Davis*, 1985]. Model 115 drifters transmitted half-hourly GPS position and temperature to polar orbiting satellites tracked by ARGOS; model 104A drifters logged data onboard at 3 min intervals and transmitted these data to satellites at half-hour intervals. Conductivity was measured with an inductive-type cell mounted on the bottom of the drifter, ~1.5 m below the surface. Sensor accuracy was ±0.02°C and ±0.2 mS cm^{-1}, for temperature and conductivity, respectively. Total salinity error was about ±0.2 psu.

[9] Hourly wind speed and direction from coastal buoys (see locations in Figure 1) were obtained from the National Data Buoy Center for the Cape Elizabeth buoy (46041, "B41") and from Destruction Island ("DESWI") for the period 2003–2006. Columbia River buoy (46029, "B29") data were collected from 1994 to 2007. In spring-summer 2006, almost no data were collected at B41. To provide wind information on the northern half of the Washington coast for May–June 2006, a regression was performed between data from B41 and DESWI (r^2 = 0.89), using coefficients determined from regression during spring-summer 2003, 2004 and 2005. Hourly wind data were used to compute wind stress, using the drag coefficient formulated by *Large and Pond* [1981]. Both hourly stress and wind were low-pass filtered in a manner similar to the water property and velocity data discussed above.

[10] Daily mean river discharge data for the Columbia River estuary were obtained from the U.S. Geological Survey for the station at Beaver Army Terminal, Quincy, Oregon for the period 1994–2007. The flow recorded at this site represents 97% of the average annual river flow at the mouth for the Columbia River; it represents >99% of the summer flow, when discharges from coastal streams are low [*Bottom et al.*, 2001].

[11] To provide upstream information on salinity in the Strait of Juan de Fuca, daily salinity data at high tide were obtained at Race Rocks (racerocks.com), a lighthouse in the eastern Strait of Juan de Fuca (location shown in Figure 1). Two outliers were removed from the data set; in each case, salinity was lower than adjacent points by 1 psu or more.

[12] Satellite sea surface temperature (SST) data were obtained from the CoastWatch West Coast Regional Node (http://coastwatch.pmel.noaa.gov) National Oceanic and Atmospheric Administration (NOAA) program. The primary source of CoastWatch data is the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA series polar orbiting weather satellites. Spatial resolution is ~1.1 km and SST is estimated to within ±0.5°C.

3. Results

3.1. Setting

3.1.1. General

[13] Variability in water properties and currents in the northern CCS is dominated by the effects of seasonal upwelling [*Hickey*, 1998]. Upwelling begins after the "spring transition," tilting isopycnals upward toward the coast, resulting in a southward baroclinic jet over the mid and outer shelf as well as over the continental slope. A northward undercurrent develops in summer over the slope and outer shelf. In the northern CCS much of this seasonal upwelling may be driven by remote winds [*Hickey et al.*, 2006]. Remote forcing is also important on scales of 2–10 days: quasi-barotropic coastally trapped waves have been shown to account for up to 100% of the variance in alongshelf velocity at mid shelf in some years and at some locations

[*Battisti and Hickey*, 1984; *Hickey et al.*, 1991]. Nevertheless, recent drifter studies show that in summer, reversals in the alongshore direction of currents are relatively rare even in the frictionally influenced near surface layer over the mid to outer shelf and over the upper slope from the Strait of Juan de Fuca to northern Oregon [*MacFadyen et al.*, 2005, 2008]. On the inner shelf, current reversals from the southward seasonal mean to northward are relatively common, a frictional response to changes in the direction of local wind stress [*Hickey et al.*, 2005]. Near surface (Ekman layer) currents in regions farther offshore also respond directly to local wind stress, moving water onshore or offshore for northward or southward wind stress, respectively.

[14] Substantial freshwater is provided to the northern CCS by the Strait of Juan de Fuca. The total riverflow during the spring freshet is on the order of 1.8×10^4 m^3 s^{-1} [*Masson and Cummins*, 2004], with the Fraser River being the primary source (about half the total flux) and the remainder contributed by other rivers in the Strait of Georgia as well as by Puget Sound. This water is mixed with inflowing deep oceanic water in shallow regions within the Strait of Georgia and also along the Strait of Juan de Fuca itself [*Masson and Cummins*, 2004]. Outflowing water from the Strait of Juan de Fuca is fresher than coastal water, but typically greater than 30.5 psu in spring and 30 psu in summer, when maximum discharge occurs [*Hickey et al.*, 1991]. The outflowing water is also high in nutrients (NO_3 >20 μM l^{-1}) due to mixing with upwelled coastal waters [*Mackas et al.*, 1980; *MacFadyen et al.*, 2008]. Fluctuations in salinity, temperature and velocity in the strait have significant fortnightly and monthly variability. These signals are a result of periods of weak mixing in the tidal passes separating the Fraser River from the Strait of Juan de Fuca. The effect is amplified if neap tides coincide with periods of southward winds: the wind stress pushes a thin surface lens of low salinity water into the Strait [*Griffin and LeBlond*, 1990; *Hickey et al.*, 1991; *Masson and Cummins*, 2000]. Detailed analysis of these pulses show that the pulse travels down the strait with about a 5 day lag between Race Rocks and the mouth of the strait [*Hickey et al.*, 1991]. Because of these time variable processes, a station just inside the eastern end of the strait (Race Rocks, see Figure 1) is usually selected to provide upstream conditions for outflowing strait water.

[15] The typical tidally averaged volume flux exiting the Strait of Juan de Fuca during the spring freshet is on the order of 10^5 m^3 s^{-1} (estimated from data at the mouth of the strait in the work of *Hickey et al.* [1991]; also see *Thomson et al.* [2007], with mid strait estimates). A portion of this water forms the northwestward flowing Vancouver Island Coastal Current [*Thomson et al.*, 1989; *Hickey et al.*, 1991]. However, in spring and summer, much of the water circulates around a seasonal eddy that forms offshore of the strait [*Tully*, 1942; *Freeland and Denman*, 1982; *Crawford*, 1988; *MacFadyen et al.*, 2005, 2008]. The water joins the southeastward flowing seasonal upwelling jet along the south side of the eddy and flows southward along the mid (early season) to outer (late season) shelf [*MacFadyen et al.*, 2008].

[16] The Columbia plume also provides freshwater to the northern CCS: riverflow in spring is $\sim 10^4$ m^3 s^{-1}, roughly half that provided to the Strait of Juan de Fuca. The tidally averaged outflow is about 1.4×10^4 m^3 s^{-1} (estimated from *Knudsen* [1900]), almost an order of magnitude smaller than the outflow from the Strait of Juan de Fuca. However, the salinity deficit of the freshwater transferred to the coastal ocean is much larger than that of the strait (S $\sim$10–20 psu [*Hickey et al.*, 2005]), so that effects on local stratification and circulation (but not on macronutrients) should exceed those of the strait. Early studies of the Columbia depict its plume as tending northward in winter and southwestward in summer [*Barnes et al.*, 1972]. In late fall and winter, Columbia plume water enters the Strait of Juan de Fuca during storms [*Holbrook and Halpern*, 1982; *Hickey et al.*, 1991; *Thomson et al.*, 2007].

[17] The recent availability of more summertime data over the shelf between the Columbia River mouth and the Strait of Juan de Fuca allowed *Hickey et al.* [2005] to show that water from the Columbia is observed in this region in summer at least 50% of the time. Because of the presence of the mean baroclinic southward flow described above, a southwest Columbia plume is generally formed during periods of upwelling-favorable winds [*Garcia-Berdeal et al.*, 2002]. The response of the Columbia to variable winds is described in the model study by *Garcia-Berdeal et al.* [2002] and confirmed by moored sensor data shown by *Hickey et al.* [2005]. During a downwelling-favorable wind event, the southwest plume moves onshore south of the river mouth. At the same time, a new plume forms north of the river mouth, trapped within $\sim$20–30 km of the coast. This plume propagates and also is advected northward by inner shelf currents that reverse during periods of downwelling-favorable winds. When winds return to upwelling-favorable, inner shelf currents reverse to southward within several hours and the shallow Columbia plume is advected offshore in the wind-driven Ekman layer. Once over the central shelf, the plume is advected farther south by the seasonal mean ambient flow.

3.1.2. Spring-Summer 2006

[18] Winds during spring 2006 were persistently upwelling-favorable throughout most of May 2006 (Figure 2). Contoured salinity sections across the shelf both north and south of the river mouth (see Figure 1 for locations) confirm that the spring transition occurred before 22 May: isohalines 40 to 200 m from the sea surface are tilted upward toward the coast in both sections, consistent with the existence of the seasonal baroclinic southward jet (Figure 3). This period of upwelling-favorable local winds is followed by three intervals of moderate downwelling-favorable winds (storms, N1, N2 and N3), with periods of weakly fluctuating or upwelling-favorable winds between the storms. Persistent upwelling-favorable winds return on 17 June (Figure 2). Outflow from the Columbia is particularly high (>10^4 m^3 s^{-1}) during much of the period of interest (shown as a black bar in Figure 2), with a maximum of 1.3×10^4 m^3 s^{-1} on 30 May (Figure 2). The influence of freshwater fluxes is observed in cross-shelf salinity sections from the beginning to the end of the study period (Figure 3). In the 22–24 May surveys, north of the Columbia mouth (GH1) the fresher water is confined to the inner shelf. The freshwater is located farther offshore south of the river mouth (CM1). By the end of the study period, plume water is much fresher and is broadly distributed across shelves both north and south of the Columbia mouth; the freshest water (23.15 psu) is located south of the river mouth.

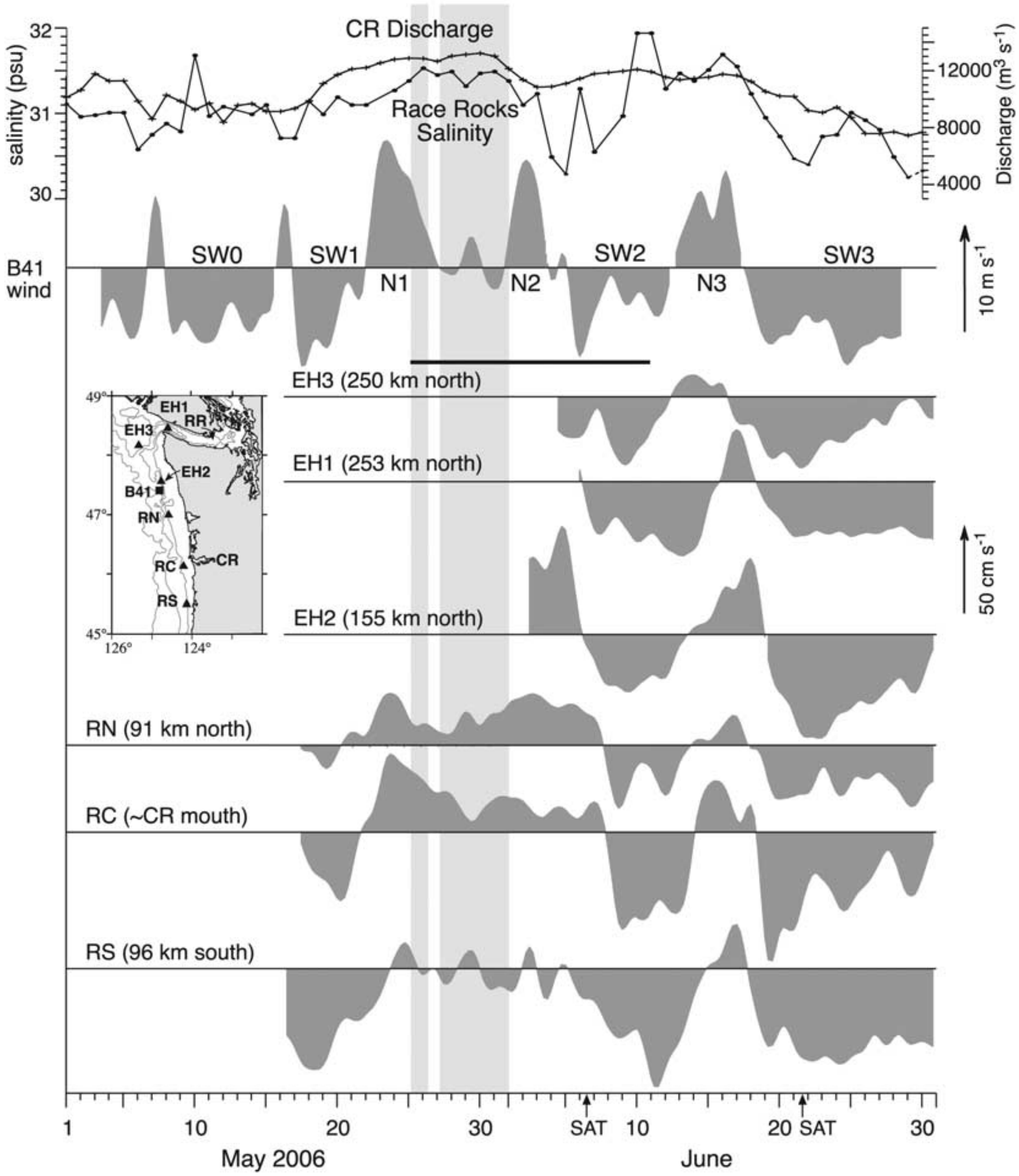

Figure 2. Time series of discharge from the Columbia River at Beaver Dam, daily averaged surface salinity at Race Rocks (RR) in the eastern Strait of Juan de Fuca, the north-south component of wind at B41 (Cape Elizabeth), and velocity at 3 m (positive northward) at selected stations north and south of the Columbia River mouth and just offshore of the mouth, as well as in the semipermanent eddy offshore of the strait. Distances in mooring labels are computed from the center of the mouth of the Columbia River. The east-west component of subtidal velocity in the mouth of the strait (EH1) (positive eastward; i.e., into the strait) is also shown. Station locations are shown on the inset map. Wind events that initiate buoyant plume events labeled in Figures 4 and 12b, as well as satellite imagery (''SAT'') and surveys discussed in the paper (two gray vertical bars) are also indicated. The black bar under the wind time series indicates the period of plume formation and interaction discussed in detail in the text.

[19] In general, alongshelf surface currents over the mid shelf (45 m bottom depth, EH2; and 70 m bottom depth, RN, RC and RS) are significant at all locations and fluctuations are generally coherent over the entire region of interest: northward during periods of northward winds, and southward during southward winds (Figure 2). This coherence extends to the entrance of the Strait of Juan de Fuca, where flow into the strait (EH1) accompanies northward alongshelf flow (EH2).

[20] The three plumes that are the focus of this paper are visible in a satellite-derived sea surface temperature from 21 June, during the period of persistent upwelling winds in late June (Figure 1). In summer, water emanating from the Strait of Juan de Fuca is colder than ambient coastal water [*Hickey et al.*, 1991; *MacFadyen et al.*, 2008]; water emanating

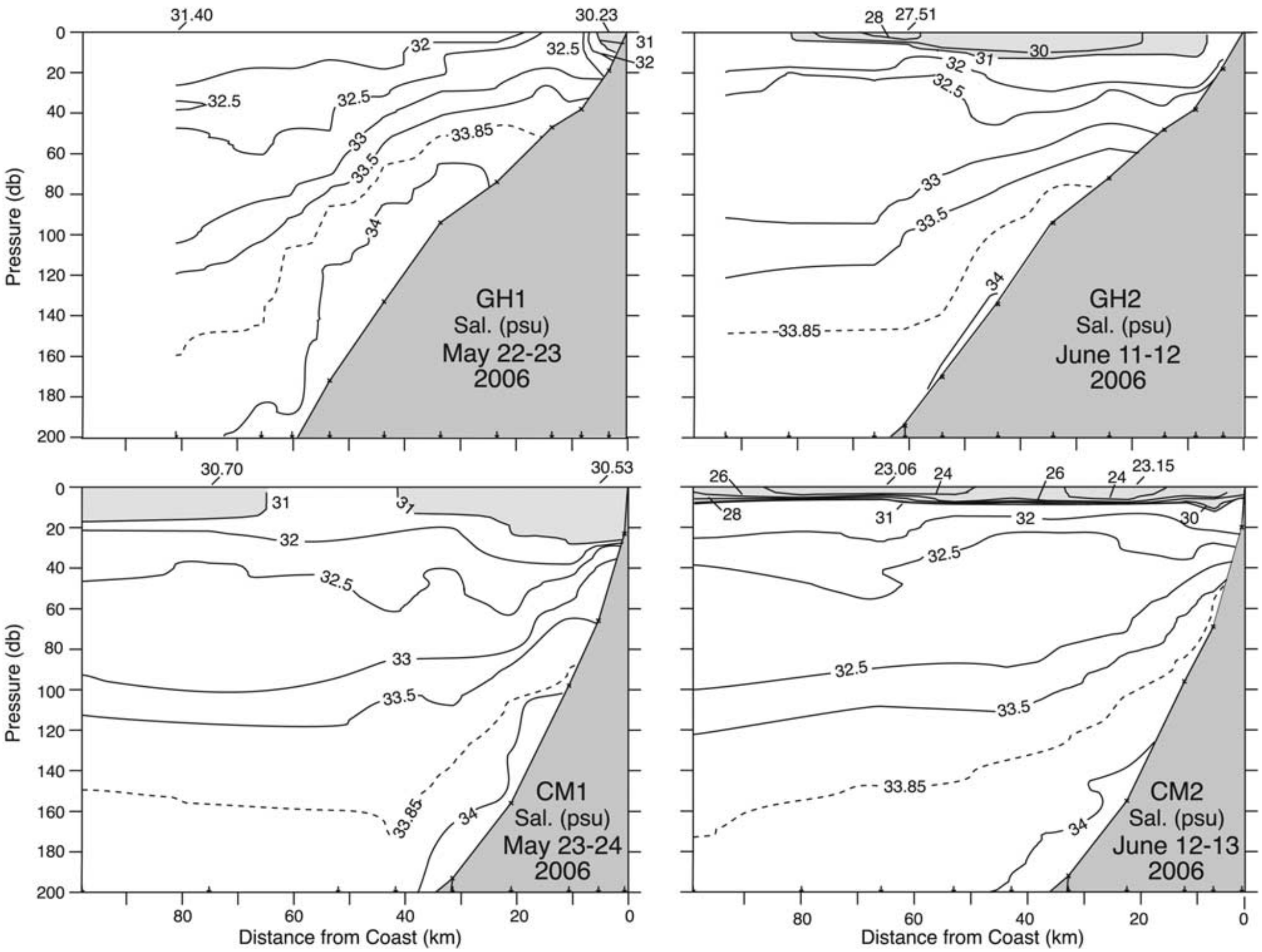

Figure 3. Contoured salinity sections along transects north (GH) and south (CM) of the river mouth (see locations in Figure 1): (left) at the onset of formation of a new north tending Columbia plume, N1 in Figures 2 and 4; and (right) after a new southwest plume has formed (SW2 in Figures 2 and 4) and merged with the old north plume. Station locations are indicated as ticks inside the *x* axis. Areas with salinity less than 31 psu are shaded to better delineate plume water. Salinity minima are noted along the top of each section.

from the Columbia is warmer than ambient coastal water [*Hickey et al.*, 2005]. In Figure 1, the plume from the Strait of Juan de Fuca is evident as the colder water emanating from the strait. Colder water is also observed in a feature offshore of the strait: this is the signature of the Juan de Fuca eddy. The cyclonic circulation associated with this feature is consistent with the yellow tendril of warmer water that delineates its perimeter. Warmer water is evident along the Washington coast. As will be confirmed below, this feature is an indication of a north tending plume from the Columbia. The third plume, a warmer feature extending southwest of the mouth of the Columbia, also originates from the Columbia.

[21] Near surface time series of salinity in the northern CCS in spring/early summer 2006 contain several minima at locations both north and south of the Columbia River mouth (Figure 4). These features are labeled in order of appearance and also as to whether they are north (N), south (S) or southwest (SW) of the mouth of the Columbia. Wind events responsible for these events (as demonstrated below) are marked with the same labels in Figure 2. Note that wind events generally precede the appearance of freshwater at downshelf locations due to the time period required for propagation and/or advection from the freshwater source [*Hickey et al.*, 2005]. Periods of low salinity are not simultaneous throughout the region. Rather, fresher water is observed roughly out of phase north and south of the river mouth. These phase lags will be discussed in detail in the sections that describe plume development in those regions. The time series show that just prior to the date of the satellite image in Figure 1 (21 June), salinity minima were observed both southwest (SW3) and north (N3) of the Columbia River mouth, consistent with the presence of both a southwest tending and a north tending plume from the Columbia at that time.

[22] Salinities in the time series north of the Columbia mouth are frequently lower than 26 psu (Figure 4). The time series of salinity at an upstream location in the Strait of Juan de Fuca (Figure 2; see Figure 1 for Race Rocks station location) demonstrates that this water could not have originated from the Strait: salinity during this period never falls below 30 psu in the eastern strait. Moreover, during

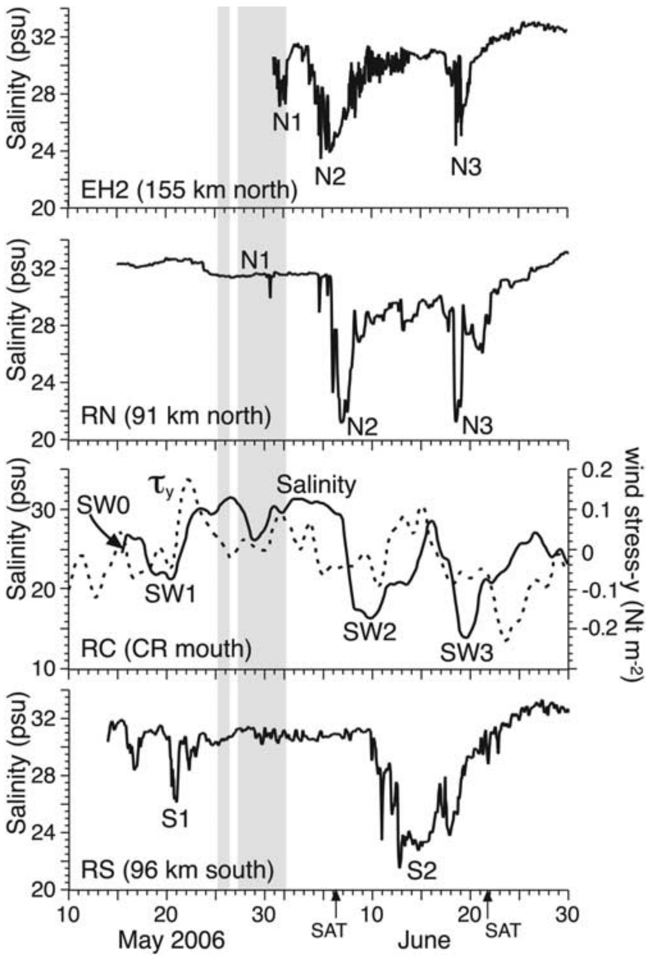

Figure 4. Time series of salinity at moorings north and south of the Columbia River mouth (hourly) and just offshore of the mouth (subtidal) (see Figure 1 for locations). Distance from the river mouth is noted in the label. The north-south component of wind stress (positive northward) from a buoy near the mouth of the Columbia (B29) is plotted on the panel near the plume mouth (RC). Note that data from EH2 are deeper (4 m) than those from RN, RC and RS (1 m) and that the salinity scale is larger for the RC mooring. Freshwater plume orientation (northward, "N"; southwest, "SW"; or southward, "S") is indicated, as well as the timing of satellite imagery ("SAT") and hydrographic surveys (two gray vertical bars).

each period of decreasing salinity at stations north of the Columbia River mouth alongshelf velocity is northward (Figure 2), providing further confirmation that the Columbia is the origin of these features.

3.2. Description of Three-Plume Development and Interaction, 22 May to 11 June

[23] The following discussion describes the development of a north tending plume from the Columbia, its northward journey into the Strait of Juan de Fuca where it interacts with the strait's outflowing plume; the development of a new southwest tending Columbia plume; and last, the journey of the now aged plume water southward back down the coast where it interacts with a new southwest Columbia plume. This period is indicated by a black bar beneath the wind time series in Figure 2.

3.2.1. Development of a North Tending Columbia Plume (N1)

[24] Time series of near surface salinity from the two moorings north of the Columbia River mouth show at least three periods of low salinity on the central Washington shelf in May–June 2006 (Figure 4). Wind and velocity data confirm that each event is observed following a period of northward near surface flow and downwelling-favorable winds (Figure 2, N1, N2 and N3). Minimum salinities are significantly lower than that observed in the Strait of Juan de Fuca (~25–28 psu at EH2 versus >30 psu at Race Rocks; Figures 2 and 4). Thus, the origin of these pulses must be either Washington coastal estuaries (Grays Harbor or Willapa Bay, see Figure 1) or the Columbia River. Because freshwater fluxes from the smaller estuaries are two orders of magnitude less than those of the Columbia [*Hickey and Banas*, 2003], the observed minima are attributed to plumes from the Columbia.

[25] A lag in minimum salinity occurs between the two northern sites for the N2 plume event, with the minimum occurring later at the more southern site. This counterintuitive lag occurs because the more southern mooring site (RN) is located in deeper water (70 m) than the more northern site (EH2, 45 m) and thus farther offshore (24 km for RN versus 17 km for EH2). Neither mooring is located on the inner shelf where the plume is concentrated during downwelling-favorable winds. Thus plumes are observed at both moorings as they spread offshore primarily during upwelling-favorable winds (typical offshore spreading rates are ~10 km d^{-1} [*Hickey et al.*, 2005]) so that plumes are frequently observed later at greater distances from the coast (e.g., N2, a 1 day lag over the 7 km distance between moorings).

[26] Two shipboard surveys of the northward plume that developed during the period 25–31 May (plume N1) confirm the connection of the low salinity features observed in the mooring time series to the Columbia (Figure 5). Survey periods are shown as shaded columns in Figures 2 and 4. The first survey was performed while winds were downwelling-favorable. Hence, although somewhat aliased, the survey provides a snapshot of a plume under development. The second survey was performed during a wind relaxation period in which winds were weak and fluctuating in direction. The plume in the first survey is trapped to the coast, with salinities as low as 28 psu on the most northern transect. Salinities increase from 26 near the river mouth to 28 psu over the 150 km alongcoast distance of the survey. In the second survey, water with salinity of 30 psu has spread farther offshore at most locations by ~10–25 km. Minimum salinity is observed offshore of the coast near the river mouth and that minimum salinity is 4 psu lower than in the first survey. The range of salinity along the coast is greater than that in the first survey, ~6 psu over 200 km.

3.2.2. Interaction of a North Tending Columbia Plume With the Juan de Fuca Strait Effluent

[27] The salinity maps from the surveys show that the north tending Columbia plume is continuous to the northern point of Washington state on 31 May, with salinities less than 28 psu on the inner shelf. On 6 June, when upwelling-favorable winds return, a satellite-derived sea surface

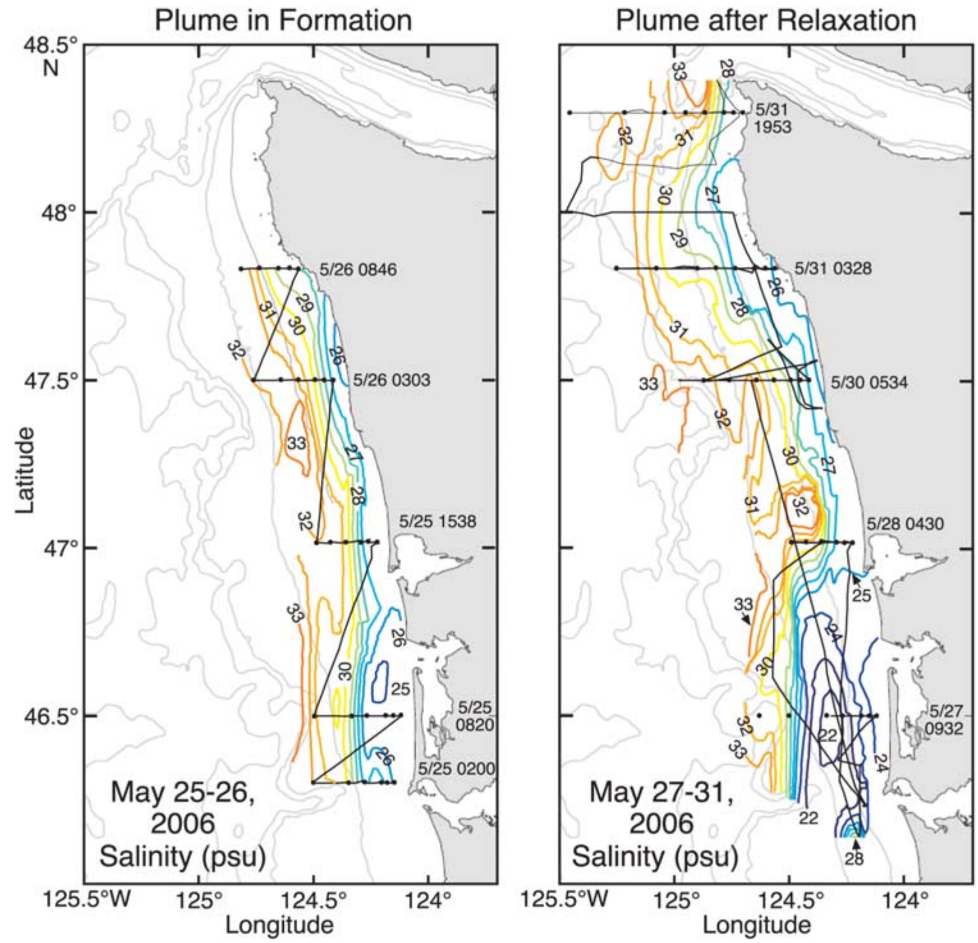

Figure 5. Plan maps of contoured salinity at 4 m during two surveys, one (left) during north plume formation, the other (right) beginning 2 days later during a wind relaxation period. Salinity is color coded such that cold colors indicate fresher water. Timing of the surveys with respect to wind, riverflow and buoyant plume events is shown in Figures 2 and 4 as two gray vertical bars. Data were obtained from CTD stations (shown as dots) as well as underway data collected along the cruise track (shown as lines). The start time of the first CTD station on each line is given to the right of each transect.

temperature image illustrates that Columbia plume water has crossed the entrance of the Strait of Juan de Fuca (Figure 6). Warmer Columbia plume water is seen in a nearly continuous band ~30 km wide from just north of the Columbia entrance almost to the north side of the Strait of Juan de Fuca. The colder water of the Juan de Fuca plume is evident inshore of the Columbia water in a narrow band adjacent to Vancouver Island. The Columbia plume appears to have become entrained in the counterclockwise Juan de Fuca eddy, apparent as the colder feature offshore of the warmer Columbia plume water. Note that an additional storm event on 1–4 June likely contributed to/enhanced the north tending plume between when it was sampled in the surveys shown in Figure 5 and the 6 June satellite imagery. This plume is labeled N2 in the salinity time series at the coastal stations (Figure 4).

[28] To illustrate the direction of surface transport during the development of this north tending Columbia plume, selected surface drifter tracks are superimposed on the satellite-derived sea surface temperature image of 6 June (Figure 6). A drifter deployed on 22 May during the first storm (N1) moves onshore in the surface Ekman layer in response to the downwelling-favorable winds. Subsequently all drifters move northward along the coast, with one drifter crossing the mouth of the strait and beaching on 31 May. Thus the drifter trajectories are consistent with northward advection of plume water and with the fact that plume water can cross the mouth of the strait, as suggested by SST in the satellite image. The two other drifters shown in Figure 6 reverse direction and move offshore at the onset of upwelling-favorable winds. These drifter trajectories are presented in the context of the complete set of drifter tracks later in this section.

[29] Interaction between the north tending Columbia plume, Strait water and the Juan de Fuca eddy can be shown explicitly by comparing salinity time series in the strait and in the eddy with salinity time series at locations on the coast, in the context of a time series of alongshelf wind (Figure 7). At the coastal site (blue, EH2) a plume is observed near 31 May after the plume that had developed during the period 23–25 May (N1) relaxes and moves offshore across the mooring site as shown in the survey maps (Figure 5). Salinity initially increases at the coastal site during the storm that follows 1–3 June (N2), because

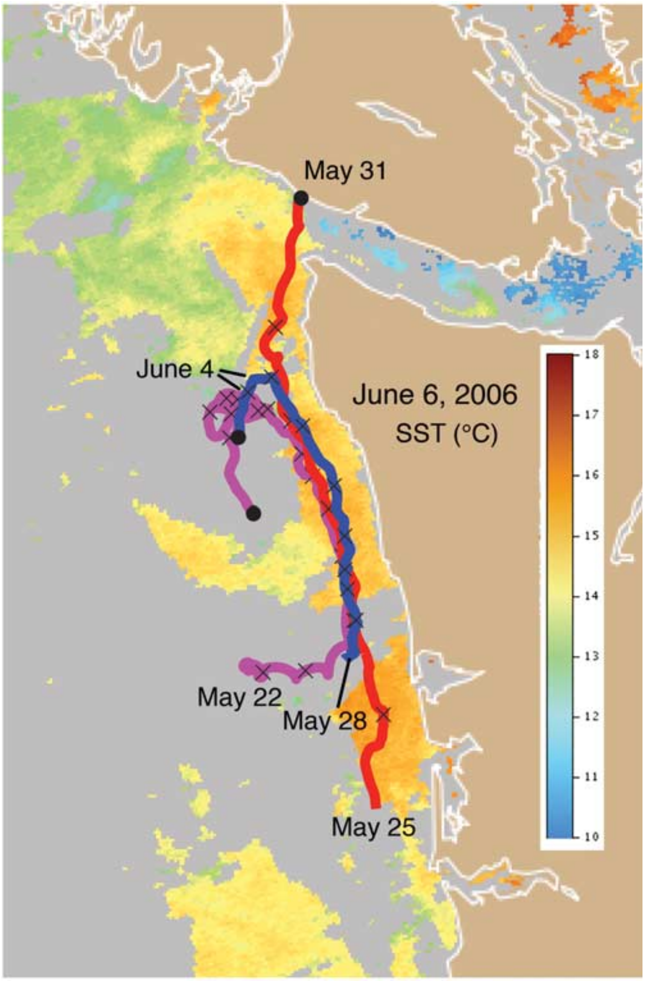

Figure 6. Satellite-derived sea surface temperature on 6 June 2006. Selected tracks of surface drifters deployed during the formation of a north tending Columbia plume 22–28 May (N1) are also shown. Daily locations are marked with crosses on the tracks. Selected dates including start times are given; end points are indicated with black dots.

the plume moves shoreward of the mooring site when it responds to the downwelling-favorable winds. The plume is observed once again at the coastal site (i.e., salinity decreases) when winds reverse to upwelling-favorable and the plume again moves offshore crossing the mooring site. The lower salinity during this second plume event is consistent with north plume enhancement (i.e., additional discharge into the plume has occurred) during the 1–3 June storm.

[30] Salinity inside the mouth of the strait (black, EH1) is consistent with an intrusion of Columbia plume water prior to 3 June, when the series begins, to 6 June, two days after winds reverse to upwelling-favorable (Figure 7). Hourly velocities at the site are upstrait, consistent with intrusion of surface ocean water into the strait during this period (not shown) as during all other periods of downwelling winds in the time series. Note that one vector in the low-passed data of Figure 2 shows this inflow explicitly (earlier data are removed by the filtering process). Salinity at the mouth of the strait (<28.5 psu) is ~3 psu less than that observed in the eastern strait (<31.5 psu at Race Rocks, Figure 2). Three days after the intrusion into the strait, salinity begins to decrease at the mooring site in the southwest corner of the Juan de Fuca eddy (red, EH3). The minimum salinity (~28.5 psu) is less than observed in the eastern strait but typical of Columbia plume water, as shown in the coastal time series. Velocities at this site are southeastward during this period as shown in the bottom panel of Figure 7. This latter result confirms that the fresher water originated from the northwest rather than from the southeast; i.e., the water did not come from direct advection from the northern Washington coast but transited around the Juan de Fuca eddy.

[31] The fate of the Columbia plume water that transited much of the coast between the Columbia mouth and the Strait of Juan de Fuca is illustrated by the pathways of surface drifters that were deployed at the onset of the north tending Columbia plume development and followed through the time period after winds changed to persistently upwelling-favorable (Figure 8). After moving onshore during 22–23 May, and then moving northward until 4–5 June, all drifters reversed direction and traveled south and offshore during the period of persistent upwelling-favorable winds. Salinities recorded at the start and end of selected drifter tracks indicate that some drifters that were deployed outside the plume (~31.5 psu) subsequently became entrained into Columbia plume water. Several drifters were tracking water of ~28 psu after the three week journey up and down the coast. In the next section we will show that these drifters and the older plume water they are tracking interact with a newly developing southwest tending Columbia plume on about 11–12 June.

[32] Note that another significant north tending Columbia plume is observed at the coastal stations in the period 18–22 June (N3, Figure 7). Salinity time series at the mouth of the strait and in the eddy confirm that this plume did not reach either the strait or the eddy like the earlier plumes (Figure 7). This conclusion is consistent with satellite-derived sea surface temperature on 21 June shown in Figure 1.

3.2.3. Development of Southwest Tending Columbia Plumes

[33] Comparison of salinity time series north of the river mouth (EH2 and RN) with that just offshore of the mouth (RC) illustrates a generally out-of-phase relationship (Figure 4). This relationship reflects the fact that southwestward plumes develop under upwelling-favorable wind conditions and northward plumes develop during downwelling-favorable wind conditions [*Hickey et al.*, 2005]. Southwestward plumes occur when inner shelf currents reverse to southward and the plume is turned offshore into the southward large scale baroclinic seasonal flow. When inner shelf currents reverse to northward during downwelling-favorable wind conditions, the northward advection reinforces the rotational tendency of plumes and a new plume forms north of the river mouth. This sequence of winds frequently leads to the existence of two plumes from the Columbia at the same time (see summary figure in the work of *Hickey et al.* [2005]).

[34] Three periods of well developed southwestward plumes (S < 25 psu) and at least one minor plume (S ~25 psu) are observed in the May–June 2006 period (Figure 4). Note that minimum hourly averaged salinities at the RC mooring (only) are 2–8 psu lower than values in the low-pass filtered

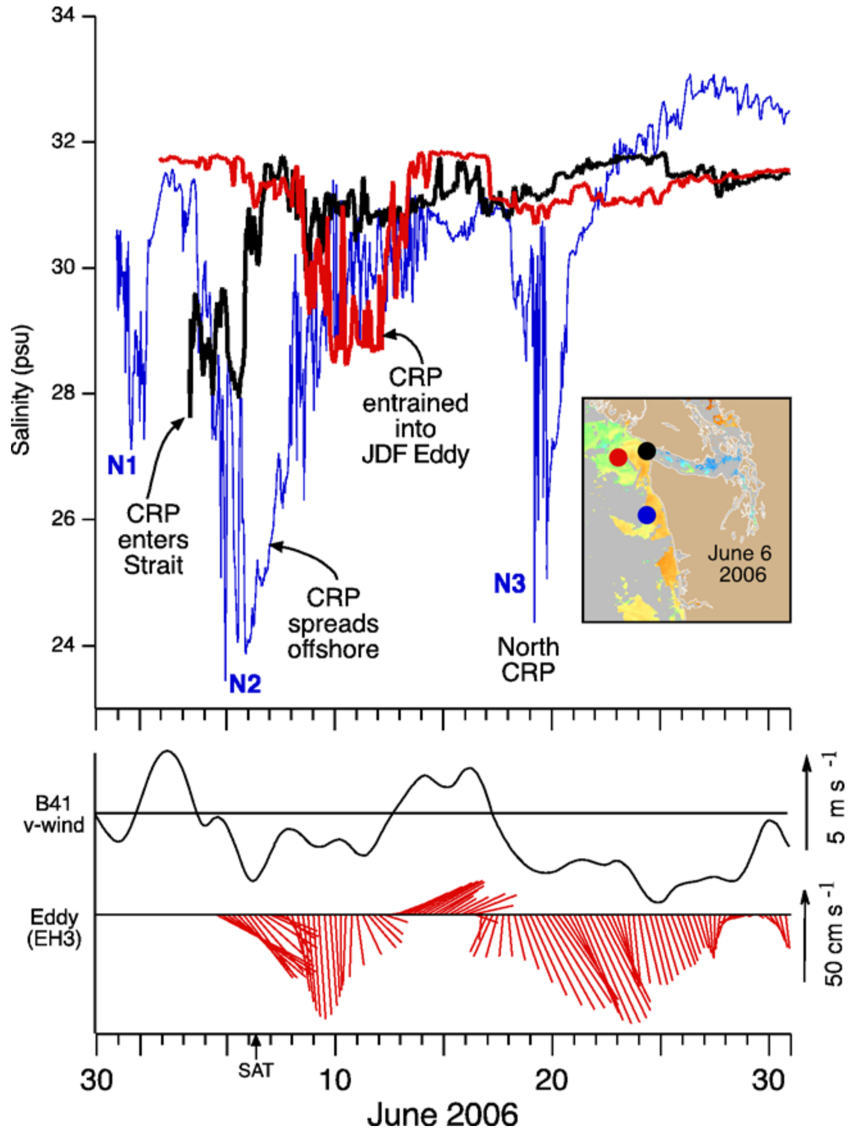

Figure 7. Hourly time series of 4 m salinity on the Washington shelf (EH2), in the mouth of the Strait of Juan de Fuca (EH1) and on the southwest edge of the seasonal eddy offshore of the Strait (EH3). Freshwater events corresponding to plumes from the Columbia are labeled as N1, N2 and N3, as in Figures 2 and 4. Locations are shown on the inset map of satellite-derived sea surface temperature for 6 June. Data are color coded on the map to distinguish locations of the time series. North-south wind at B41 (positive northward) on the northern Washington shelf as well as subtidal vector velocity at 3 m at the eddy location (positive northward and onshore) are also shown.

salinity shown in Figure 4. The southwest plume near 20 May (SW1) is a result of the extended period of upwelling-favorable winds during most of May (Figure 2). This period is followed by moderate northward winds leading to the development of the northward plumes seen on the shelf north of the river mouth (N1, N2). Persistent upwelling returns on 4 June, resulting in the formation of a persistent and moderately fresh southwestward plume (SW2).

[35] Salinity time series near the Columbia River mouth illustrate that no major southwest tending plume had been present for over two weeks prior to 7 June (RC, Figure 4). Thus this period presented an ideal opportunity to study the development and aging of a new southwest tending plume following the transition to persistent upwelling-favorable winds. An intensive shipboard drifter/water property study was therefore initiated on 7 June. Four surface drifters were deployed just outside the river mouth in a north-south line at maximum ebb tide at about 9:00 GMT (Figure 9). Immediately following deployment the ship executed a north-south transect, obtaining hydrographic data at a depth of 4 m. The "pack" of drifters was followed in real time using a GPS-tracking device onboard ship. Three additional transects across the plume were made over the next two days, in each case beginning at a location just behind the centroid of drifter locations. The success of this technique is demonstrated by the fact that drifter locations plotted at the end of transect 14 (black filled circles) lie very close to the transect line (Figure 9). Mid shelf regional ambient surface currents

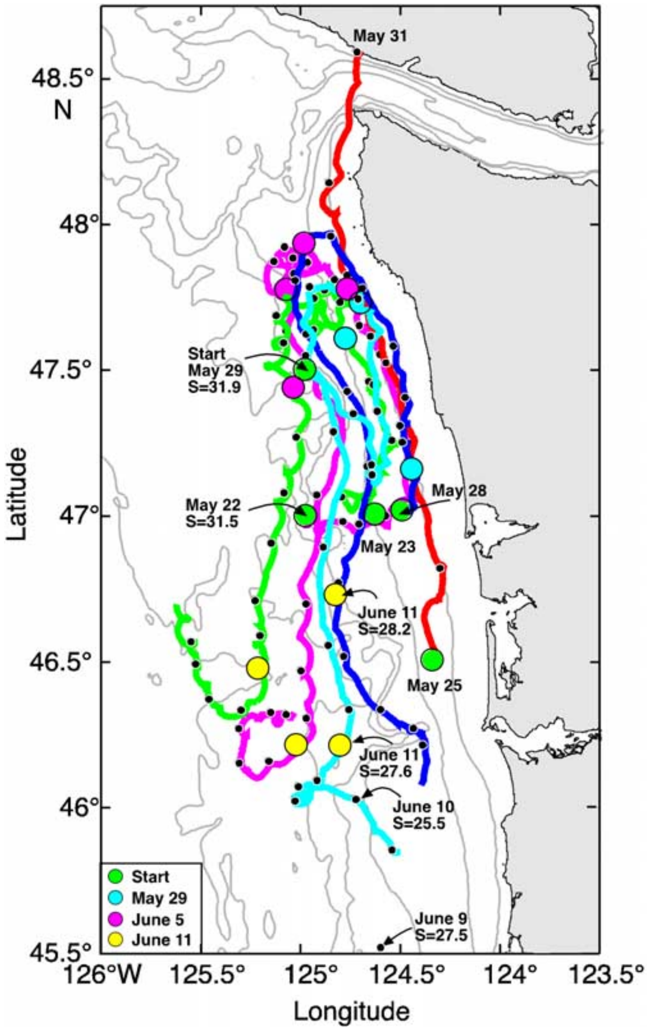

Figure 8. Tracks of surface drifters deployed during the formation of north tending plumes from the Columbia (N1 and N2) and the development of a new southwest tending plume from the Columbia (SW2). Black dots on tracks mark each day. Drifters moved onshore at the onset of north plume development, traveled north along the coast, and reversed direction to southward at the onset of upwelling-favorable winds on 4–5 June. Selected dates, including start times, are noted on the tracks. Salinities are noted on several occasions, either at a drifter site or at a CTD site. Bottom contours are 50, 100, 200, 500, 1000, and 2000 m.

during this experiment were southward (Figure 2). Thus, as shown by three drifter tracks, the plume turned southward after emerging on the ebb tide (Figure 9). The northernmost drifter executed an anticyclonic turn before crossing the mouth region heading southward. Drifters moved southward and slightly offshore at about 50 km d^{-1} over the next two days. The development and longevity of the new southwest plume is captured by the surface salinity time series at the mooring just offshore of the river mouth (Figure 4, SW2).

[36] Salinity time series from the drifters (not shown) indicate that drifters were deployed initially in water of salinity 1.5–6.5 psu, from south to north across the estuary mouth. Salinity increased rapidly to ~16 psu over about 2 h. Salinity continued to increase, with strong tidal fluctuations of about 1–2 psu over the next 12 h. Subsequent increases were relatively smooth and constant over the next 2 days, with final salinities of about 26 psu at the end of 9 June. No major fronts were observed to suggest that the drifters crossed the plume front (all salinity offsets after 8 June, 0500 were less than 1 psu).

[37] The location of water from the new plume along the salinity transects in Figure 9 is not visually obvious, with the exception of the first two transects, where only a narrow or a single minimum occurs. If we make the assumption that the drifters were tracking New water, i.e., water less than a day old, it is apparent that the New water does not likely account for all the minima in the figures; nor is the New water necessarily even the freshest water on a transect. To identify sources of the other minima, upstream conditions for Aged and Recent (1–2 days since exiting the estuary) north tending plume water were determined. From the maps shown in Figure 5 and from the salinities along tracks of drifters that traveled north and then returned south in the plume (Figure 8), Aged water (plume water residing north of the river mouth for more than ~14 days) has a salinity of about 28 psu. A CTD section (LB Line) ~20 km north of the river mouth (see location in Figure 9) sampled one day before the new plume emerged, suggests a salinity of ~21 psu is typical of Recent plume water (Figure 10). Using these water property characteristics, the minima on the transect data in Figure 9 were designated as either Aged or Recent water. The locations of these minima were then plotted on the drifter track figure along with the locations of real drifters that were tracking the New water. These designations are consistent with the flow direction indicated by the drifter tracks; i.e., Aged and Recent waters lie along reasonable pathways from their estimated origins. Note that Aged water had not yet reached the southernmost transect.

[38] Surface nitrate data confirm the differentiation of New and Recent water masses as described in the preceding paragraph. The nitrate maximum on Transect 11 is 7.3 μM, a typical concentration during a period when the river is providing nitrate from the watershed [*Bruland et al.*, 2009]. On Transect 12, nitrate is 5.6 and 7.3 μM for the left and right New water extrema, respectively. On Transect 13, the extrema labeled Aged, Recent and New have surface nitrates of 0.7, 0.9 and 3.6 μM, respectively. The highest value corresponds to the location of the pack of drifters, consistent with their continuing to track New water. In the last transect, New water has a nitrate of only 0.4 μM, less than that for Recent water as labeled. Fluorescence data (not shown) indicate almost a doubling in the New plume water between transects 13 and 14, consistent with a nitrate drawdown from several μM to near zero over that time interval (about 1 day). Moreover, for the drifters to have escaped shoreward of the new plume axis and for New water to be the extremum that has the higher nitrate and lower salinity (labeled Recent), drifters would have had to move counter to the direction of surface currents. Surface currents are directed offshore (not shown) as well as southward (see Figure 2) during this period at 3 m at RN, RC and RS, as expected for the southward wind conditions.

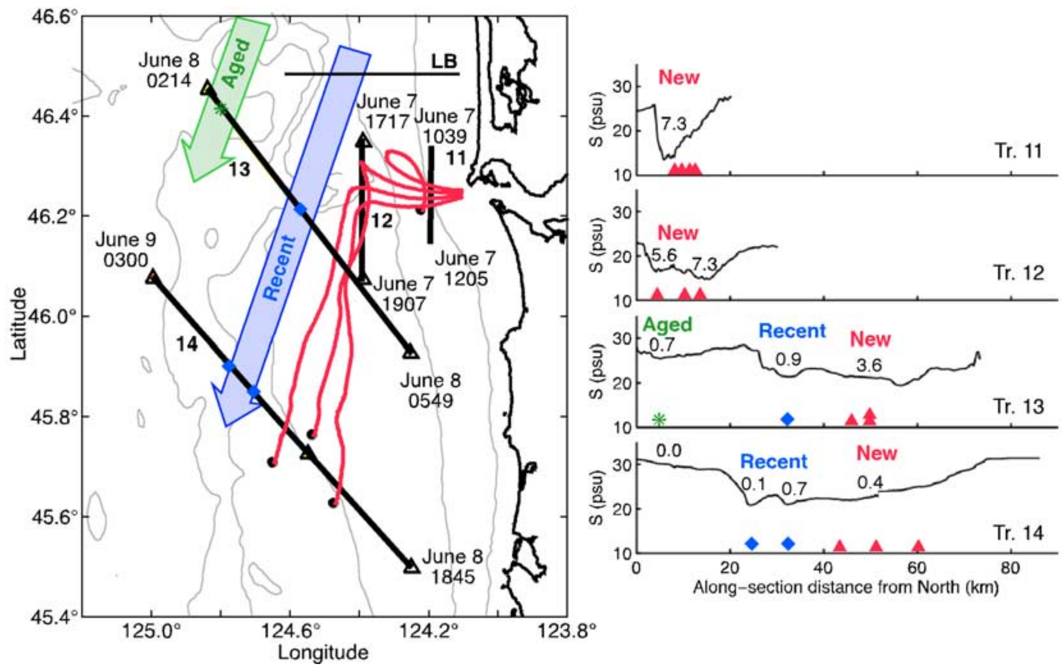

Figure 9. (left) Tracks of surface drifters deployed across the mouth of the Columbia River on 7 June 2006 to follow an emerging new plume. Underway salinity at 4 m on several cross plume transects is also shown; the start and end times of each transect are noted on the figure. Black filled circles on the drifter tracks near Transect 14 indicate the drifter location at the time of the end of the transect. Locations of Aged, Recent and New water types as identified on the right panel are shown with colored symbols. (right) Salinity versus distance from the north end of each transect. Drifter locations as they crossed each transect are shown with red triangles (New water). Recent (blue) and Aged (green) water are also identified (see text). Values of surface NO_3 extrema are given on the transects.

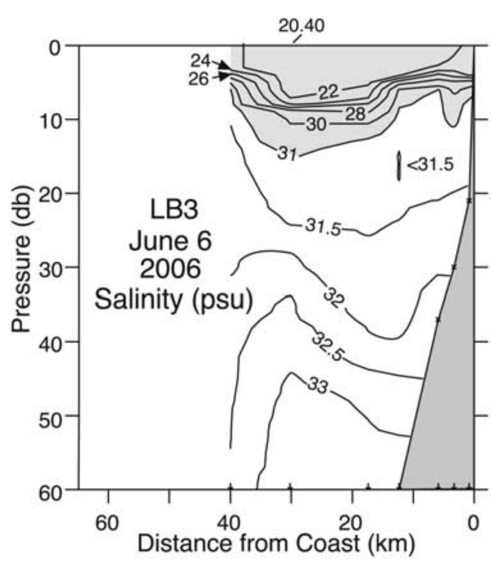

Figure 10. Contoured salinity section across the shelf off Long Beach, Washington, on 6 June (see location in Figure 9). Station locations are indicated as ticks inside the x axis. Areas with salinity less than 31 psu are shaded to better delineate plumes. The section provides the upstream salinity condition for Recent plume water, used in the analyses in Figure 9.

[39] The fate of the Columbia plume water that interacted with the Strait of Juan de Fuca cannot be directly assessed with drifter data. The earliest date that plume water impacted the mooring in the southwestern portion of the eddy (EH3) was 8 June (Figure 7). If 3 m north-south velocities at EH3 or EH2 are used to estimate advective transport, the Juan-de-Fuca-modified water would not reach the latitude of the Columbia mouth until about 23 June. This lengthy estimated transit time occurs because the 13–17 June storm reverses near surface flow from southward to northward for several days at both moorings (see Figure 2). Although currents reverse at the three mid to inner shelf mooring sites, prior studies in this region during an early fall period suggest that currents over the outer shelf and slope do not reverse from southward to northward during storms [*MacFadyen et al.*, 2005]. Indeed, hydrographic sections from 12 June show that deeper isohalines are sloped upward toward the coast (Figure 3) consistent with the presence of a southward baroclinic shelf break jet just prior to the storm. Also, results from a regional model of the CCS (Naval Research Laboratory coastal ocean model, NCOM) show strong southward flow throughout this period (see http://www7320.nrlssc.navy.mil/ccsnrt/). Assuming that currents did not reverse over the outer shelf in the time period of interest, and using the speed of a shelf break drifter during the 4–11 June upwelling period ($\sim$24 km d^{-1}) to represent typical speeds in this area, we would predict that the Juan-de-Fuca-influenced water would arrive at the latitude of RN on about 15 June and at the river mouth on about 18 June.

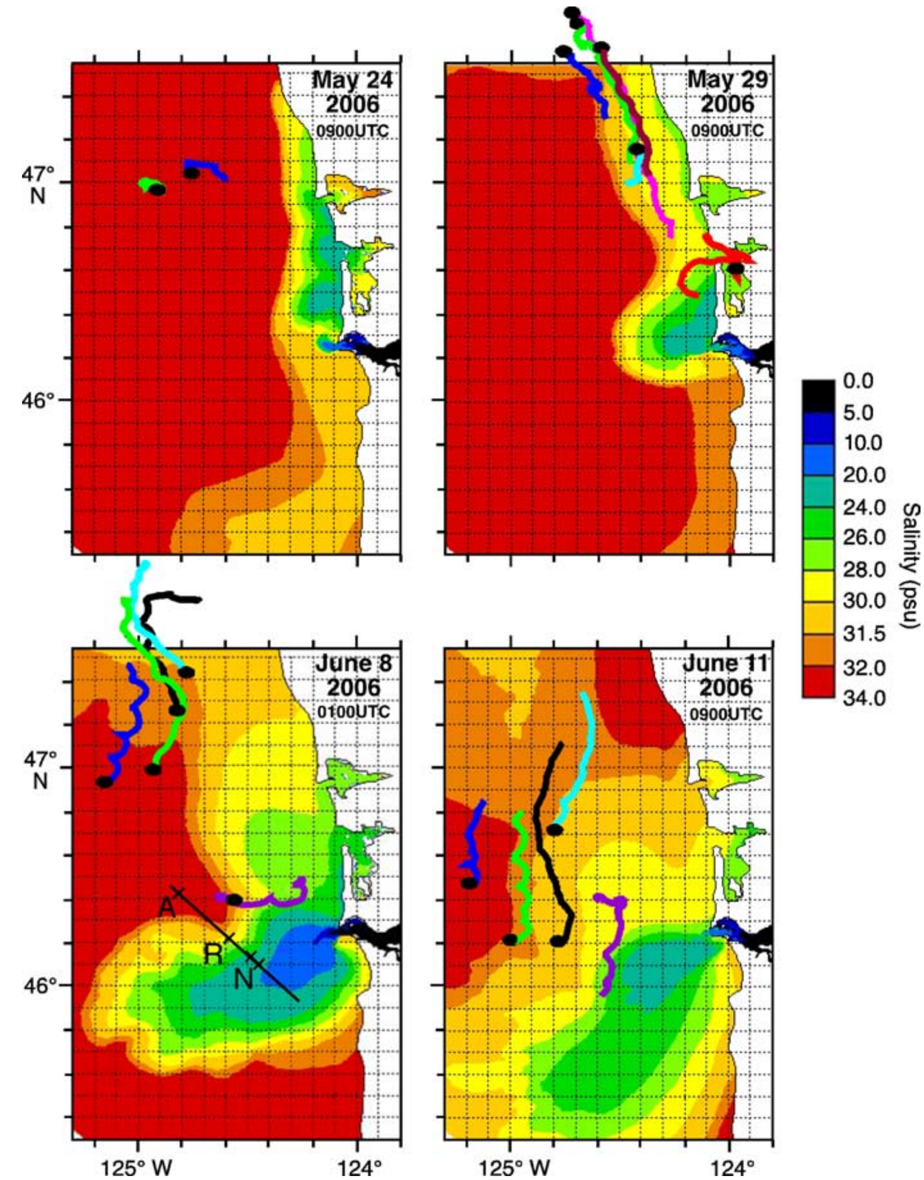

Figure 11. Surface salinity derived from the SELFE model on selected dates during May–June 2006. Surface drifter tracks for the 3 days preceding the date of the image are shown on each panel. Black dots indicate position at the time of the model map. A cross-plume transect line (Transect 13) is shown on the 8 June map. The transect was sampled 5 h after the time of the map. Locations of New, Recent and Aged water, as defined by analyses shown in Figure 9, are indicated by N, R and A, respectively.

3.2.4. Interaction of North and Southwest Tending Columbia Plumes (24 May to 11 June)

[40] The sequential development of northward and southward tending plumes can be visualized in a time series of surface salinity maps derived from a regional numerical model (Figure 11). The model results are one day forecasts of the salinity field sent in real time to the survey ship during RISE cruises. This model (SELFE [*Zhang and Baptista*, 2008]), a finite volume model, incorporates boundary conditions from the data-assimilating 10 km global NCOM model and a wind forecast from the regional MM5 atmospheric model [*Tinnis et al.*, 2006]. In situ comparisons made during cruises suggests that the model represents the salinity field reasonably well near the river mouth: in particular, it represents the movement of the plume in response to local winds well enough for practical use.

[41] The model maps show the development of the north tending Columbia plume in late May (24 May), followed by the almost complete erosion of any south tending plume (29 May). Real surface drifters have been superimposed on the model salinity fields, with tracks shown for a three day period prior to the date of the map. Drifters are color coded so that their progress can be traced from map to map. Drifters in the water on 24 May have moved shoreward and northward by 29 May in response to the downwelling-favorable winds during 24–25 May. Model salinities suggest that the drifters appear to have been entrained into the Columbia plume. Following the transition to persistent

upwelling-favorable winds on 5 June a new southwest tending Columbia plume develops as detailed above. Water from the north plume (Recent and some Aged as we show below) moving southward along the coast now interacts with newly emerging southwest plume water, forming a "stocking" shaped plume (8 June). The pack of drifters has moved southward, but has also moved offshore. One drifter (purple track) appears to be deflected offshore by the northern edge of the plume. By 11 June this southwest tending plume is well developed; salinity time series in Figure 4 show that this plume persists for about one week. Drifters continue to move southward as the upwelling-favorable winds continue.

[42] To determine the area on the model salinity maps occupied by the newly emerging plume, Transect 13 from the drifter study of the new southwest plume is plotted on the model map from 8 June. The transect data were obtained 1–5 h after the model salinity map. The model plume appears to be oriented more southward than the observed plume. The location of the New water and Aged water masses as estimated from the drifter/transect data shown in Figure 9 suggests that only the darkest blue water mass is truly New water at that time. The green and yellow water appears to be Recent and the red water is likely the Aged water that transited over 150 km up and then down the coast over a period >2 weeks. If we spatially average model areas with their water type defined by the transect data, the results suggest that over 90% of the water in the southwest tending plume on 8 June is water that has resided previously on the Washington coast.

3.2.5. Frequency of Springtime Plume Interactions

[43] It is well known that intrusions of Columbia plume water into the Strait of Juan de Fuca occur frequently in fall and winter [*Holbrook and Halpern*, 1982; *Hickey et al.*, 1991; *Thomson et al.*, 2007]. In that season, the resulting water, mixed with strait effluent, is exported northwestward along the British Columbia coast in the seasonal ambient currents, with no return pathway southward to the northern California Current. After the spring transition, two features develop that change the export pathways: the Juan de Fuca eddy, and the southeastward baroclinic shelf jet [*MacFadyen et al.*, 2005, 2008]. Thus the buoyant plume water can return southward over northern CCS shelves after its interaction with Strait water.

[44] To examine the frequency of Columbia plume intrusions into the Strait in spring, data at the same three sites shown in Figure 7 for 2006 are displayed for the years 2003–2005 (Figure 12a). For clarity, the data have been low-pass filtered. With the exception of the coastal site, the filtering has minimal effect on resulting time series as surface layers in both the strait and eddy regions are vertically well mixed, so that high frequency fluctuations are minimal. Data at Race Rocks are provided as an upstrait salinity condition for Strait outflow (Figure 12b). In all four years shown, salinity at Race Rocks exceeds 30 psu in the period being considered. In contrast, we note that Columbia plume water observed at mid shelf along the Washington coast (EH2) is generally several psu less than 30 psu (Figure 4).

[45] When comparing the time series in Figure 12a to identify salinity intrusions, it is important to note that salinity time series at the mouth of the strait (and, at times, in the eddy) are subject to large amplitude (~0.5–1 psu) neap-spring fluctuations. These fluctuations need to be distinguished from Columbia plume intrusions. The seasonal onset of this phenomenon is apparent at Race Rocks in 2003 data, with salinity minima near 10 June and 25 June (Figure 12b). The neap spring effect is apparent in the data at the mouth of the strait in all four years shown. The amplitude of the pulses increases from spring to summer as runoff from the Fraser River increases and winds become more persistently southward. Complete seasonal time series at the mouth of the strait are shown by *MacFadyen et al.* [2008].

[46] To definitively identify Columbia plume intrusions into the strait, we established three stringent requirements: (1) a plume must be observed at the coastal site; (2) to ensure that the coastal plume has its origins south of the site, northward wind stress must be observed prior to the coastal plume observation; and (3) minimum salinity at the mouth of the strait must be less than 30 psu, the overall minimum at Race Rocks. These criteria are clearly met only in late May 2005 (Figure 12a). The minimum salinity is less than 27 psu at the coastal site and in the mouth of the strait, and minimum salinity in the eddy 5 days later is ~29 psu. Overall, this event is very similar to that in 2006.

[47] Coastal plumes are observed in both 2003 and 2004 (Figure 12a). However, in 2004 no intrusion is observed in the strait mouth (EH1). In 2003, salinity is significantly lower in the eddy than at the mouth of the strait for about 20 days at the beginning of the time series. Late in that period, a coastal plume is observed. However, the minimum that follows at the mouth of the strait is likely the signature of a low salinity neap pulse rather than a Columbia plume intrusion. Model hindcasts (SELFE, not shown) indicate that the Juan de Fuca region salinity was very fresh at this time. A regional survey in ECOHAB PNW during this period shows a strip of low salinity water extending from north of the strait southward past Grays Harbor [*MacFadyen et al.*, 2008]. The origin of this water remains unclear.

[48] Thus, data available suggest that springtime intrusions of Columbia water into the Strait of Juan de Fuca, and subsequent entrainment into the Juan de Fuca eddy occur in about half the recent years sampled. Comparison of intrusion events with alongshelf wind stress near the mouth of the Columbia (B29) and Columbia outflow provides a rough estimate of some of the conditions required for such interaction. Both 2005 and 2006 interaction events took place during or following periods of very high Columbia River outflow (>10^4 m^3 s^{-1}) and relatively high wind stress (>0.15 N m^2). Both riverflow and alongshelf wind stress on the southern Washington shelf were much weaker in the years when no clear interaction events were observed. In 2004, the wind stress that likely formed the observed coastal plume was about 0.15 N m^{-2} and outflow was about 7.5 × 10^3 m^3 s^{-1}. In the 2003 event coastal plume wind stress was 0.15 N m^{-2} and Columbia outflow was 10^4 m^3 s^{-1}.

[49] To extend these analyses further, alongshelf wind stress and Columbia outflow were examined during the period 1994–2002 for events similar to those of 2005 and 2006. Periods likely to have significant Columbia plume/Juan de Fuca eddy interactions occurred in 1995, 1998 and

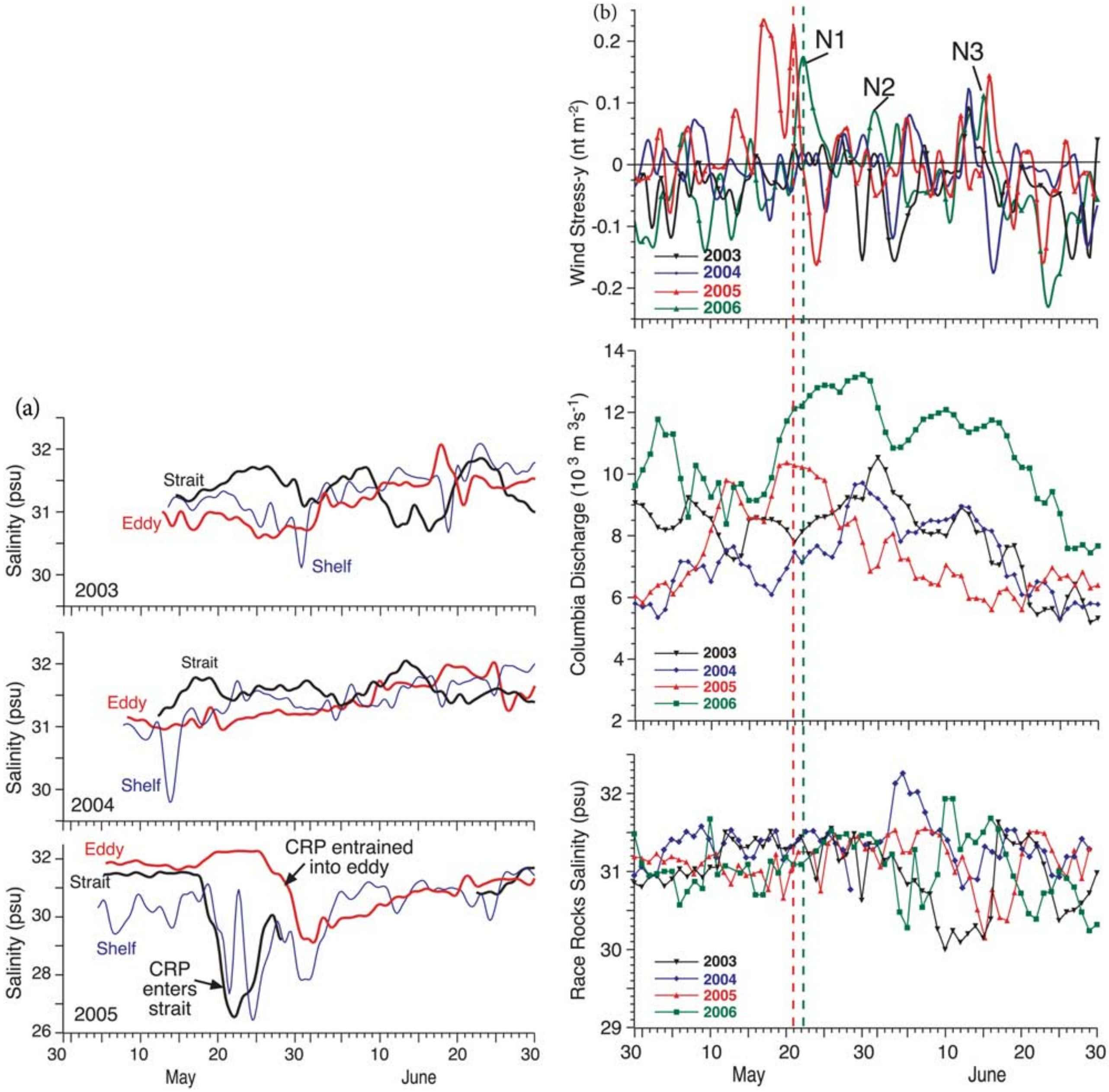

Figure 12. (a) Subtidal time series of 4 m salinity at locations on the shelf (EH2), in the mouth of the strait (EH1) and in the Juan de Fuca eddy (EH3) in 2003, 2004 and 2005. Time series are at the same locations as data for 2006 shown in Figure 7. Note that mooring EH2 is located farther offshore in 2003 than in the other years (bottom depth 89 m versus 45 m), so that freshwater plumes likely have a weaker signature at the 2003 location. (b) North-south wind stress at B29, Columbia discharge at Beaver Dam and daily averaged surface salinity in the eastern Strait of Juan de Fuca for 2003–2006. Vertical color coded dashed lines indicate Columbia plume/Juan de Fuca plume interaction events identified in Figure 7 (2006) and Figure 12a (2005). Periods in 2006 when the Columbia plume tends northward, identified in Figure 4, are also indicated (N1, N2 and N3).

1999; i.e., in roughly half the years sampled, similar to the recent period studied in more detail.

4. Discussion and Summary

[50] This paper combines moored sensor, satellite, hydrographic and drifter data from two multiyear studies: RISE, which focused on the region near the Columbia River plume, and ECOHAB PNW, which focused on the region bracketing the Strait of Juan de Fuca. This rich data set is used to delineate the distribution and time variability of freshwater plumes in the northern CCS. One major conclusion is that outflow from the strait, and the seasonal eddy associated with the outflow, can play a major role in redirecting plume

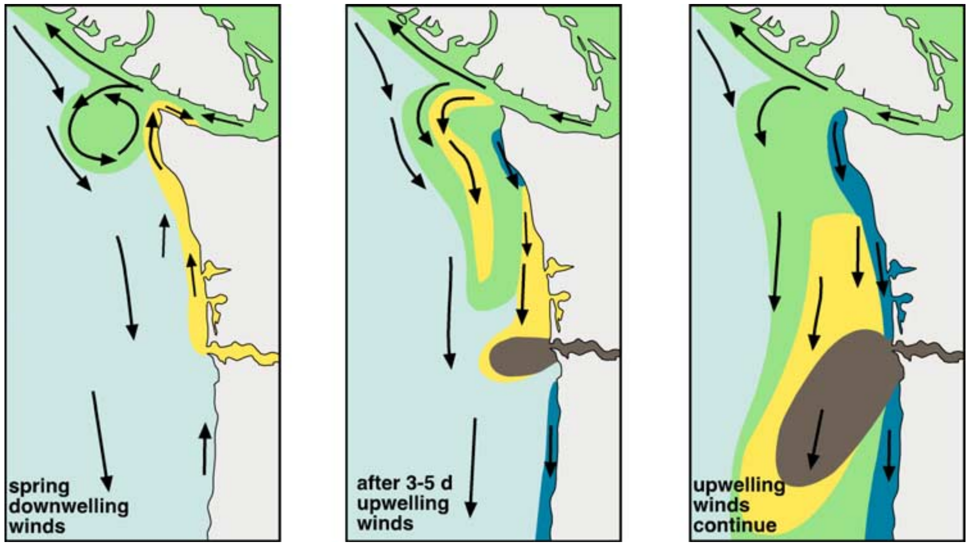

Figure 13. Cartoon summarizing the time-dependent interaction of the three buoyant plumes in the northern CCS in spring-early summer: the north plume from the Columbia (yellow), the plume from the Strait of Juan de Fuca (green) and the southwest plume from the Columbia (brown). Surface salinity patterns are shown at the end of relatively strong downwelling-favorable winds, 3–5 days after the onset of upwelling-favorable winds and after several more days of persistent upwelling-favorable winds. Newly upwelled water is indicated in dark blue. Surface currents are shown with black arrows.

water from the Columbia River in spring and early summer. Under conditions of large downwelling-favorable wind stress and large Columbia outflow, the Columbia plume can become entrained in this eddy, extending its regional residence time by several weeks. The existence of this eddy is itself critically dependent on outflow from the strait as well as on the baroclinic shelf break jet set up by upwelling winds after the spring transition [*Foreman et al.*, 2008]. A second major conclusion is that the north tending plume originating from the Columbia River interacts strongly with the more traditionally recognized southwest tending plume from the Columbia under upwelling-favorable wind conditions, such that the new southwest plume often contains primarily aged water from the older north tending plume.

[51] The major buoyant plume related processes in the northern CCS in spring to early summer are summarized in a cartoon (Figure 13). The surface salinity patterns of the three plumes described in this paper as well as upwelled water are color coded during a period of relatively strong downwelling-favorable winds, after 3–5 days of upwelling-favorable winds and after several more days of persistently upwelling-favorable winds. During downwelling-favorable wind conditions, the colder freshwater plume from the Strait of Juan de Fuca (whose freshwater largely originates in the Fraser River) extends along Vancouver Island, and the Juan de Fuca eddy is retentive [*MacFadyen et al.*, 2005, 2008]. The north tending plume from the Columbia, depicted here for the case of high riverflow and relatively large northward wind stress discussed in this paper, extends along the coast north of the river mouth and enters the Strait of Juan de Fuca. Near surface currents are northward on the inner and mid shelf and onshore over the mid to outer shelf; currents farther offshore remain southward (although onshore) if the baroclinic jet is sufficiently strong. At the onset of upwelling-favorable wind conditions, the Juan de Fuca eddy opens up, as the geostrophic constraint is broken by currents in the wind-driven frictional layer [*MacFadyen et al.*, 2008]. Columbia water and Juan de Fuca water stream southward in the southward baroclinic jet. Because inner shelf, frictionally dominated currents are southward, new water emerging from the Columbia can break the rotational tendency of the plume to turn right. New plume water is therefore entrained into the southward regional currents. The north tending plume begins to spread offshore due to strong wind-driven frictional currents, which are enhanced in the vertically compressed Ekman layer of a shallow plume [*Hickey et al.*, 1998]. Deep upwelled water appears in regions that are not “capped” by buoyant plumes (see discussion of “capping” by *Hickey et al.* [2005]). The Aged and Recent plume waters begin to move south, merging with the New plume, forming a stocking shaped plume (in yellow). After several days of upwelling-favorable wind conditions, the Juan-de-Fuca-redirected water from the Columbia and Aged and Recent north plume waters have all merged with the New plume, which continues to fill with new water on each tide. Upwelled deep water may be observed at the sea surface all along the coast, although our experience on 10 cruises over a four year period indicates that this occurs rarely off the Washington coast.

[52] Why are these buoyant outflows and their interactions important? While a detailed discussion of the effects of buoyant plumes is beyond the scope of this paper, several of the most important effects are summarized here. From an ecosystem perspective, the outflow from the Strait of Juan de Fuca may provide the dominant control on regional nutrient supply and plankton growth, not only to the southern British Columbia coast [*Mackas et al.*, 1980] but to the entire northern CCS [*Hickey and Banas*, 2008]. The nutrients supplied by the Strait, being controlled by fortnightly estuarine timescales, are much more persistent than those provided by coastal upwelling in this region where

nutrient supply is shut down by reversals to downwelling-favorable winds every 2–10 days [*Crawford and Dewey*, 1989; *MacFadyen et al.*, 2008]. The nutrients are also spread much farther offshore at the sea surface before biological utilization occurs (~60 km versus ~10 km) than nutrients supplied by conventional coastal upwelling [*MacFadyen et al.*, 2008]. This massive nutrient source and resulting large phytoplankton blooms provide upstream conditions for shelves in the northern CCS.

[53] Just as the nutrients in the Strait of Juan de Fuca are supplied by upwelling of deep oceanic waters that are entrained into the surface outflow from the strait, nutrients in upwelling deeper waters are entrained into the Columbia plume in the plume "lift off" region [*Conomos et al.*, 1972; *Bruland et al.*, 2009]. Typical nutrient concentrations in the plume during upwelling conditions are 16–19 μM NO_3 at a salinity of 20 psu and 15 nm of dissolved iron [*Bruland et al.*, 2009]. Offshore movement of the Columbia plume, particularly during upwelling winds, moves the nutrient-rich upwelled water farther offshore than would occur via conventional upwelling in the absence of a plume. In periods of downwelling-favorable wind conditions and precipitation, the Columbia sometimes supplies nutrients from its watersheds, with typical values of 2.5–6 μM NO_3 and 3–7 nm dissolved iron in the plume [*Bruland et al.*, 2009]. Our results demonstrate that salinity in north tending plumes from the Columbia increases by as much as 6 psu in about 200 km, consistent with substantial mixing of deeper water into the surface-trapped plume. These plumes typically overlie nutrient rich water, suggesting that nutrients may also be supplied to such plumes as they transit along the coast and are advected back and forth over the shelf by fluctuating winds.

[54] The existence of river plumes also significantly modifies the physical environment in a coastal area: stratification, heat, light, cross and alongshelf circulation can all be affected, and the modified environment, in turn, changes elements of the ecosystem from plankton to juvenile salmon [*Hickey and Banas*, 2003, 2008]. For example, the existence of fronts at plume boundaries will cause localized jets in associated currents, and fronts may also provide a barrier to cross-shelf transport [*Hickey et al.*, 2005; *Banas et al.*, 2008]. In general, prior data and modeling illustrate that alongcoast currents on the inner shelf are almost doubled in speed by the presence of a north tending plume [*Hickey et al.*, 1998; *Garcia-Berdeal et al.*, 2002]. Cross-shelf circulation is also affected, a result of the tendency for geostrophic flow around the light water of the plume [*Hickey et al.*, 1998]. The enhanced offshore movement of plumes increases cross-shelf transport over regions without plumes [*Banas et al.*, 2008]. During upwelling, the depth of the cross-shelf return flow that balances offshore Ekman transport occurs at shallower depths with stronger stratification [*Lentz and Chapman*, 2004]: return flow has been observed as shallow as ~15 m over the Washington shelf in the presence of highly stratified plume water [*Hickey*, 1989]. Such modification of cross-shelf transport pathways may have important effects on phytoplankton growth. For example, plankton may be able to move onshore just under a plume, without experiencing light limitation and having access to a rich nutrient supply during such transit. Details of these and other impacts of river plumes are the subject of our ongoing research.

[55] **Acknowledgments.** Water property data collection and drifter deployments were supported by grant OCE-0239089 to B. Hickey from the National Science Foundation (NSF) as part of the Coastal Ocean Processes RISE Program. Deployment of moored arrays was supported by grants from NSF to E. Dever (OCE-0238021) as part of RISE and by grants to B. Hickey from the Center for Sponsored Coastal Ocean Research of NOAA (NA17OP2789) and NSF (OCE-0234587) as part of ECOHAB PNW. Analysis was also supported by these grants. The authors would like to thank the captains and crews of the R/V *Wecoma* (RISE surveys and drifter studies as well as mooring deployment and recovery) and Canadian Coast Guard Vessels *John P. Tully* and *Vector* (deployment and recovery of ECOHAB PNW moorings). Rafe Kudela graciously supplied Coastwatch satellite data, and Antonio Baptista supplied model output during our cruises. Ken Bruland, Maeve Lohan and Tina Sohst were responsible for collection of nutrient data, graciously supplied for this paper. Moorings at EH2 and EH3 were sited in the Olympic National Marine Sanctuary under National Marine Sanctuary Permits OCNMS-2003-02 and 2006–004. This is contribution 26, 19 and 280 of the RISE, ECOHAB PNW and ECOHAB programs, respectively. The statements, findings, conclusions, and recommendations are those of the authors and do not necessarily reflect the views of the NSF, NOAA or the Department of Commerce.

References

Banas, N. S., P. MacCready, and B. M. Hickey (2008), The Columbia River plume as cross-shelf exporter and along-coast barrier, *Cont. Shelf Res.*, doi:10.1016/j.csr.2008.03.011.

Barnes, C. A., A. C. Duxbury, and B.-A. Morse, (1972), Circulation and selected properties of the Columbia River effluent at sea, in *The Columbia River Estuary and Adjacent Ocean Waters*, edited by A. T. Pruter and D. L. Alverson, pp. 5–80, Univ. of Wash. Press, Seattle.

Battisti, D., and B. M. Hickey (1984), Application of remote wind forced coastal trapped wave theory to the Oregon and Washington coasts, *J. Phys. Oceanogr.*, *14*, 887–903.

Bottom, D. L., C. A. Simenstad, A. M. Baptista, D. A. Jay, J. Burke, K. K. Jones, E. Casillas, and M. H. Schiewe (2001), *Salmon at river's end: The role of the estuary in the decline and recovery of Columbia River salmon*, 271 pp., Natl. Mar. Fish. Serv, Seattle, Wash.

Bruland, K. W., M. C. Lohan, A. M. Aguilar-Islas, G. J. Smith, B. Sohst, and A. Baptista (2009), Factors influencing the chemistry of the near-field Columbia River plume: Nitrate, silicic acid, dissolved Fe, and dissolved Mn, *J. Geophys. Res.*, doi:10.1029/2007JC004702, in press.

Conomos, T. J., M. G. Gross, C. A. Barnes, and F. A. Richards (1972), River-ocean nutrient relations in summer, in *The Columbia River Estuary and Adjacent Ocean Waters*, edited by A. T. Pruter and D. L. Alverson, pp. 151–175, Univ. of Wash. Press, Seattle.

Crawford, W. R. (1988), The use of Loran-C drifters to investigate eddies on the continental shelf, *J. Atmos. Oceanic Technol.*, *5*, 671–676.

Crawford, W. R., and R. K. Dewey (1989), Turbulence and mixing: Sources of nutrients on the Vancouver Island continental shelf, *Atmos. Ocean*, *27*(2), 428–442.

Davis, R. E. (1985), Drifter observations of coastal surface currents during CODE: The method and descriptive view, *J. Geophys. Res.*, *90*, 4741–4755.

Foreman, M. G. G., W. Callendar, A. MacFadyen, B. M. Hickey, R. E. Thompson, and E. Di Lorenzo (2008), Modeling the generation of the Juan de Fuca Eddy, *J. Geophys. Res.*, *113*, C03006, doi:10.1029/2006JC004082.

Freeland, H. J., and K. L. Denman (1982), A topographically controlled upwelling center off southern Vancouver Island, *J. Mar. Res.*, *40*, 1069–1093.

Gan, J., and J. S. Allen (2005), Modeling upwelling circulation off the Oregon coast, *J. Geophys. Res.*, *110*, C10S07, doi:10.1029/2004JC002692.

Garcia-Berdeal, I., B. M. Hickey, and M. Kawase (2002), Influence of wind stress and ambient flow on a high discharge river plume, *J. Geophys. Res.*, *107*(C9), 3130, doi:10.1029/2001JC000932.

Griffin, D. A., and P. H. LeBlond (1990), Estuary/ocean exchange controlled by spring-neap tidal mixing, *Estuarine Coastal Shelf Sci.*, *30*, 275–297.

Hickey, B. M. (1989), Patterns and processes of circulation over the shelf and slope, in *Coastal Oceanography of Washington and Oregon*, edited by M. R. Landry and B. M. Hickey, pp. 41–109, Elsevier, Amsterdam, Netherlands.

Hickey, B. M. (1998), Coastal oceanography of western North America from the tip of Baja California to Vancouver Island, in *The Sea*, vol. 11, edited by K. H. Brink, and A. R. Robinson, chap. 12, pp. 345–393, John Wiley, New York.

Hickey, B. M., and N. S. Banas (2003), Oceanography of the Pacific Northwest coastal ocean and estuaries with application to coastal ecosystems, *Estuaries*, *26*(48), 1010–1031.

Hickey, B. M., and N. S. Banas (2008), Why is the northern California Current so productive?, *Oceanography*, *21*(4), 90–107.

Hickey, B. M., R. E. Thomson, H. Yih, and P. H. LeBlond (1991), Velocity and temperature fluctuations in a buoyancy-driven current off Vancouver Island, *J. Geophys. Res.*, *96*(C6), 10,507–10,538.

Hickey, B. M., L. J. Pietrafesa, D. A. Jay, and W. C. Boicourt (1998), The Columbia River plume study: Subtidal variability in the velocity and salinity fields, *J. Geophys. Res.*, *103*, 10,339–10,368.

Hickey, B., S. Geier, N. Kachel, and A. MacFadyen (2005), A bi-directional river plume: The Columbia in summer, *Cont. Shelf Res.*, *25*, 1631–1656.

Hickey, B., A. MacFadyen, W. Cochlan, R. Kudela, K. Bruland, and C. Trick (2006), Evolution of chemical, biological and physical water properties in the northern California Current in 2005: Remote or local wind forcing?, *Geophys. Res. Lett.*, *33*, L22S02, doi:10.1029/2006GL026782.

Holbrook, J. R., and D. Halpern (1982), Winter-time near surface currents in the Strait of Juan de Fuca, *Atmos. Ocean*, *20*, 327–339.

Knudsen, M. (1900), Erneuerung der unteren Wasserschhichte in der Ostee, *Ann. Hydrogr. Mar. Meteorol.*, *28*, 586–590.

Large, W. G., and S. Pond (1981), Open ocean momentum flux measurements in moderate to strong winds, *J. Phys. Oceanogr.*, *34*, 2444–2457.

Lentz, S. J., and D. C. Chapman (2004), The importance of nonlinear cross-shelf momentum flux during wind-driven coastal upwelling, *J. Phys. Oceanogr.*, *21*(8), 1186–1201.

MacCready, P., N. S. Banas, B. H. Hickey, E. P. Dever, and Y. Liu (2008), A model study of tide- and wind-induced mixing in the Columbia River Estuary and Plume, *Cont. Shelf Res.*, doi:10.1016/j,csr.2008.03.015.

MacFadyen, A., B. M. Hickey, and M. G. G. Foreman (2005), Transport of surface waters from the Juan de Fuca Eddy region to the Washington coast: Implications for HABs, *Cont. Shelf Res.*, *25*, 2008–2021.

MacFadyen, A., B. M. Hickey, and W. P. Cochlan (2008), Influences of the Juan de Fuca Eddy on circulation, nutrients, and phytoplankton production in the northern California Current System, *J. Geophys. Res.*, *113*, C09022, doi:10.1029/2007JC004620.

Mackas, D. L., G. C. Louttit, and M. J. Austin (1980), Spatial distribution of zooplankton and phytoplankton in British Columbian coastal waters, *Can. J. Fish. Aquat. Sci.*, *37*(10), 1476–1487.

Masson, D., and P. F. Cummins (1999), Numerical simulations of a buoyancy-driven coastal countercurrent off Vancouver Island, *J. Phys. Oceanogr.*, *29*, 418–435.

Masson, D., and P. F. Cummins (2000), Fortnightly modulation of the estuarine circulation in Juan de Fuca Strait, *J. Mar. Res.*, *58*, 439–463.

Masson, D., and P. F. Cummins (2004), Observations and modeling of seasonal variability in the Straits of Georgia and Juan de Fuca, *J. Mar. Res.*, *62*, 491–516.

Thomson, R. E., B. M. Hickey, and P. H. LeBlond (1989), The Vancouver Island Coastal Current: Fisheries barrier and conduit, in *Effects of Ocean Variability on Recruitment and an Evaluation of Parameters Used in Stock Assessment Models*, edited by R. J. Beamish and G. A. McFarlane, *Can. Spec. Publ. Fish. Aquat. Sci.*, 265–296.

Thomson, R. E., S. Mihaly, and E. A. Kulikov (2007), Estuarine versus transient flow regimes in Juan de Fuca Strait, *J. Geophys. Res.*, *112*, C09022, doi:10.1029/2006JC003925.

Tinnis, S. W., R. E. Thomson, C. F. Mass, and B. M. Hickey (2006), Comparison of MM5 and meteorological buoy winds for the west coast of North America, *Atmos. Ocean*, *44*(1), 65–81.

Tully, J. (1942), Surface non-tidal currents in the approaches to Juan de Fuca Strait, *J. Fish. Res. Board Can.*, *5*, 398–409.

Zhang, Y.-L., and A. M. Baptista (2008), SELFE: A semi-implicit Eulerian-Lagrangian finite-element model for cross-scale ocean circulation, *Ocean Modell.*, *21*(3–4), 71–96.

E. Dever, College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331, USA.

S. Geier, B. Hickey, and N. Kachel, School of Oceanography, University of Washington, Seattle, WA 98195, USA. (bhickey@u.washington.edu)

R. McCabe, Department of Aviation, University of New South Wales, Sydney, NSW 2052, Australia.