

Wind-induced plume and bloom intrusions into Willapa Bay, Washington

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Abstract

The physical oceanography and chlorophyll distribution in Willapa Bay and the adjacent coastal ocean were measured during an upwelling–downwelling wind cycle in late May 1999. Coastal conditions were determined shipboard during two sets of five cross-shelf transects conducted 4 d apart, and instrument moorings simultaneously recorded wind velocity in the nearshore zone and biophysical water properties within Willapa Bay. The results demonstrate that estuarine physical oceanography and chlorophyll concentrations were determined by processes occurring in the nearshore ocean, and these in turn were forced by variation in wind stress. At the start of the study period, southerly winds produced downwelling conditions that forced the Columbia River plume against the coast, and low salinity water was advected into Willapa Bay. This water was relatively low in chlorophyll ($<2 \text{ mg m}^{-3}$). As the winds switched to an equatorward direction, coastal upwelling ensued and the Columbia plume was replaced by cold, salty water nearshore. A phytoplankton bloom exceeding 10 mg m^{-3} was generated on the shelf with its core located 10 to 40 km from the estuarine mouth. The upwelling-favorable winds then relaxed, and the bloom was apparently advected across the shelf to the coast and subsequently into Willapa Bay, where instruments recorded pulses of chlorophyll entering the estuary on flood tides. Weak downwelling conditions were prevalent for the next several days, and the Columbia River plume returned to the coast where it mixed with the chlorophyll-enriched waters in the nearshore before entering the estuary. These results demonstrate that primary productivity generated in coastal waters can be transported to estuaries, where it is likely an important yet episodic food source for estuarine organisms.

The vertical and horizontal concentration of suspended phytoplankton is generally heterogeneous in estuaries, and the large resulting temporal variation in concentration at a given site is due to the prevailing circulation patterns (e.g., Cloern et al. 1989; Roegner 1998). Sessile suspension-feeding organisms have limited feeding zones and depend on the advection of seston for their food supply (Muschenhiem 1987). Determining the factors controlling this spatiotemporal variation in phytoplankton supply is critical for under-

standing benthic–pelagic coupling and the structure of estuarine food webs.

Phytoplankton in estuarine systems can have an autochthonous or allochthonous origin. In the presence of adequate light, in situ production is controlled mainly by nutrient input from either land or ocean sources and is strongly modified by estuarine circulation patterns (Monet 1992; Cloern 1996, 1999). Alternatively, phytoplankton can be transported to estuarine regions by advection with riverine or marine water. However, freshwater phytoplankton tend to lyse when exposed to saline waters, often leading to decreases in chlorophyll concentration as the river water they reside in mixes with estuarine water (e.g., Lara-Lara et al. 1990). From the marine side, large inputs of oceanic phytoplankton to estuarine systems have not been commonly reported. For most estuaries studied to date, variation in estuarine phytoplankton abundance appears due mainly to autochthonous production supported by riverine nutrient pathways (Mitsch 1994), which in many systems are subject to anthropogenic enrichment (Cloern 2001).

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In contrast, recent studies on processes affecting outer coast estuaries of the Pacific Northwest (PNW) have revealed systems that are affected strongly by oceanic conditions (Roegner and Shanks 2001; Hickey et al. in press). This is particularly true during summer when freshwater inputs are minimal and estuaries acquire characteristics of the near-shore ocean. PNW estuaries interface with the California Current, an eastern boundary current where ocean productivity is largely determined by wind-forced coastal upwelling that supplies nutrients to the photic zone. Upwelling dynamics in this region are relatively well understood (Huyer 1983; Hermann et al. 1989). Equatorward winds induce offshore Ekman transport that results in the vertical transport of nutrient-rich water to the surface, and an upwelling front often separates upwelled water near the coast from less dense surface water further offshore. The distance of the upwelling front from the coast is a function of bottom topography and wind stress, but during active upwelling, net surface transport is generally directed offshore and this causes phytoplankton biomass to be concentrated away from the coast (Small and Menzies 1981). However, water properties over the shelf respond rapidly to variation in wind speed and direction, and during periods of reduced wind stress or poleward winds, fresher, warmer water floods back toward shore (Hickey 1989). This process might cause the cross-shelf transport of suspended material. Sustained poleward winds result in downwelling conditions, during which surface waters converge near the coast, and upward transport of nutrients, and hence phytoplankton production, is reduced.

A second important influence of the wind on the coastal oceanography of the PNW is the position of the Columbia River plume, which is usually delineated by the 31 psu (practical salinity unit) isohaline. Both observations (Hickey et al. 1998) and model studies (Garcia-Berdeal et al. in press) show that the plume orientation changes rapidly with variation in the equatorward wind stress. During upwelling-favorable winds, the plume thins and tends to the southwest off the Oregon coast, well seaward of the shelf. During downwelling-favorable winds, the plume thickens and converges on the Washington coast and tends north or northwest. The transition between these two states is initiated within hours of change in wind stress (Garcia-Berdeal et al. in press).

Pacific Northwest coastal estuaries tend to be shallow and, because of the large proportion of intertidal areas, are well flushed by tidal action and baroclinic circulation. The result is that oceanic processes have a strong effect on the variation of estuarine physical and biological water properties (Roegner and Shanks 2001; Hickey et al. in press). In this paper, we address processes affecting physical oceanographic parameters and chlorophyll concentrations in Willapa Bay, Washington, a large coastal estuary notable for producing over 50% of the region's oysters (primarily *Crassostrea gigas*). We use a combination of shipboard sampling of the coastal ocean and concurrent measurements from moored instruments on the shelf and in the estuary to document tidal- and event-scale links between the estuary and nearshore zone.

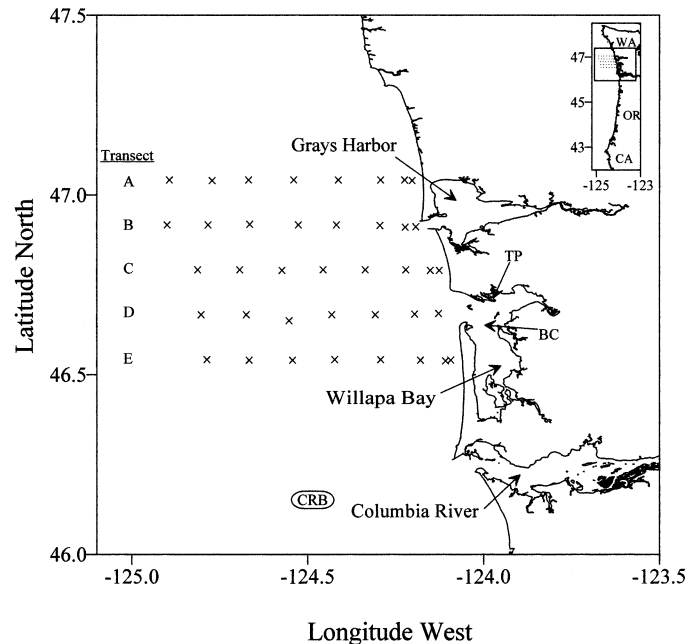


Fig. 1. Study area showing locations of cruise transects (A–E), the offshore NOAA weather buoy (CRB), tidal station at Toke Point (TP), and estuarine instrument mooring at Bay Center (BC). Inset shows study area in the regional context.

Methods

Study site—The study area comprises Willapa Bay and the adjacent ocean bounded by 46.5–47.2°N and 125.0–124.3°W (Fig. 1). Willapa Bay has a surface area of 347 km², is 55% intertidal, and has a tidal prism of 0.72 km³ (Hickey et al. in press). Its major axis is oriented north–south with the mouth of the estuary located at the northwest corner. Nine rivers and several sloughs empty into the estuary resulting in both north–south and east–west salinity gradients. Offshore, the 100-m isobath resides from 20 to 35 km from the coast.

Wind forcing—Alongshore wind stress ($N m^{-2}$) was calculated from wind velocity vectors measured at the Columbia River Bar weather buoy (Buoy 46029; 46.12°N, 124.50°W). Data were acquired from the National Data Buoy Center Web page (<http://www.ndbc.noaa.gov>). Poleward wind stress (positive values) results in downwelling conditions along the Washington coast, and equatorward winds are favorable for upwelling. The time series is plotted for the period day of year (DOY) 135–165, 1999. (All dates are expressed in DOY format, where DOY 135.5 is 1200 h on 15 May).

Oceanography of the nearshore zone—The coastal ocean off southern Washington was surveyed from the trawler *Lady Kaye* along a grid of five cross-shelf transects (A–E) extending from 1 to 80 km offshore (Fig. 1). Stations were 1.8–9.25 km apart, and the transect lines bracketed the Willapa Bay and Grays Harbor estuaries. The grid pattern was sampled twice in late May 1999: Survey 1 from DOY 143.4

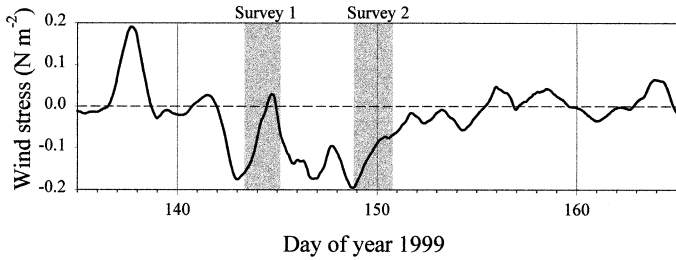


Fig. 2. Time series of northward wind stress from the Columbia River bar buoy. The cruise periods are indicated by the gray shaded sections. Positive and negative northward wind stress values are indicative of downwelling and upwelling conditions, respectively.

to 145.1 and Survey 2 from DOY 148.9 to 150.7. At each station, a Sea-Bird 25 CTD (conductivity, temperature, depth) meter with fluorometer and oxygen sensor was lowered to within 5 m of the bottom on the shelf and to 100 m elsewhere. However, displayed data are confined to the upper 40 m because water properties varied little below this depth. The data are presented as cross-shelf transects and surface plots at depths of 2, 5, 10, and 20 m.

Estuarine instrument moorings—Within Willapa Bay, time series of salinity, temperature, and fluorescence were recorded at 0.25-h intervals by a Sea-Bird 16 CT equipped with a WetLabs WetStar fluorometer. The instrument was moored at Bay Center (123.9°N, 46.6°W) near the mouth of the estuary (Fig. 1), and the sensors sampled water at a depth of 1 m. Hourly water level records from the Toke Point NOAA station located northeast of the estuarine mouth (123.9°N, 46.7°W) were acquired from the NOAA CO-OPS Web page (<http://www.opsd.nos.noaa.gov>). The time series are plotted for the period DOY 140–165, 1999.

Results

Wind stress—The time series of wind stress during the period surrounding the cruise dates shows generally downwelling conditions punctuated by two upwelling events (Fig. 2). The week preceding Survey 1 was a period of low wind stress, except for a 2-d period of strong downwelling-favorable conditions. Just prior to Survey 1, these conditions reversed to strong upwelling-favorable winds, and Survey 1 samples were made during relaxation from this 2-d event. Strong upwelling-favorable winds subsequently returned and persisted for the next 4 d, and Survey 2 samples were collected during relaxation from this wind event. Thus, both ocean surveys occurred during periods of relaxation from upwelling-favorable winds, but upwelling was more sustained during the period preceding Survey 2. The postcruise period was characterized by reduced and generally downwelling-favorable winds.

Oceanography of the nearshore zone—Survey 1: The cross-shelf salinity transects during Survey 1 revealed that the Columbia River plume was adjacent to the coast and extended north past the mouths of both Grays Harbor and Willapa Bay estuaries (Fig. 3). Low-salinity plume water

was present in the surface layer to a distance of ~60 km from shore, and the 31–32 psu isohalines resided between 10 and 20 m (Fig. 3A). Sea surface temperature (SST) exceeded 13°C throughout the survey area, and the thermocline, indicated by the 10 and 11°C isotherms, remained between 10 and 30 m, except for thin inshore outcrops in Transects B and C (Fig. 3B). The chlorophyll distribution in both plume and nearshore water was patchy, and concentrations generally remained below 2 mg m⁻³ (Fig. 3C). The core of the plume water was >80% saturated with oxygen (Fig. 3D). The presence of the Columbia River plume nearshore is generally associated with downwelling conditions.

Survey 2: Survey 2 transects showed surface water attributes consistent with recent, strong upwelling. The Columbia River plume was displaced from the coast and was only apparent offshore in the southernmost transects (Fig. 4A). Water >31 psu upwelled nearshore, and surface salinity generally decreased with distance from the coast (Fig. 4A), whereas SST values decreased to between 10.5 and 11.5°C on the shelf with warmer water offshore (Fig. 4B). A phytoplankton bloom was evident in the upwelled water, with a maximum concentration of 10.3 mg m⁻³ (Fig. 4C). The core of the bloom (>6 mg m⁻³) was centered about 10 m deep and extended from 10 to 40 km offshore, whereas lower chlorophyll concentrations were found immediately adjacent to the coast. The area of oxygen saturation increased from the Survey 1 distribution and exhibited close correspondence to the area of the bloom (Fig. 4D).

Horizontal distribution of plume and bloom: A comparison of the horizontal distribution of salinity and chlorophyll by depth for the two surveys reveals the dynamic nature of PNW upwelling systems (Fig. 5). Each survey took ~1.75 d to complete, and they were separated by a 4-d period. During Survey 1, the Columbia River plume was clearly evident as the dominant nearshore feature in the upper 20 m. The plume had an alongshore orientation during Survey 1 (following bottom topography), but isohalines switched to a predominantly cross-shelf orientation during Survey 2, when the inshore edge of the plume could be seen in the southwestern sections of the grid (Fig. 5). The chlorophyll distribution exhibited a similar spatial pattern, with low values in the plume water during Survey 1 and high concentrations in water >31 psu during Survey 2. The phytoplankton was concentrated between 2 and 20 m deep and 10–40 km from shore. These observations suggest we captured a large advective event, with the northward-tending plume waters of Survey 1 moving offshore and to the south during Survey 2 and being replaced in the north and northeast by upwelled subsurface water. This upwelled water supported the phytoplankton bloom.

Estuarine mooring data—Time series of salinity, temperature, and fluorescence from Bay Center and of water level from Toke Point exhibited significant temporal variation (Fig. 6). Spectral analysis of the time series shows that all measured constituents varied strongly at the M₂ tidal frequency (data not shown), indicating the importance of tidal advection on circulation patterns in Willapa Bay. The range

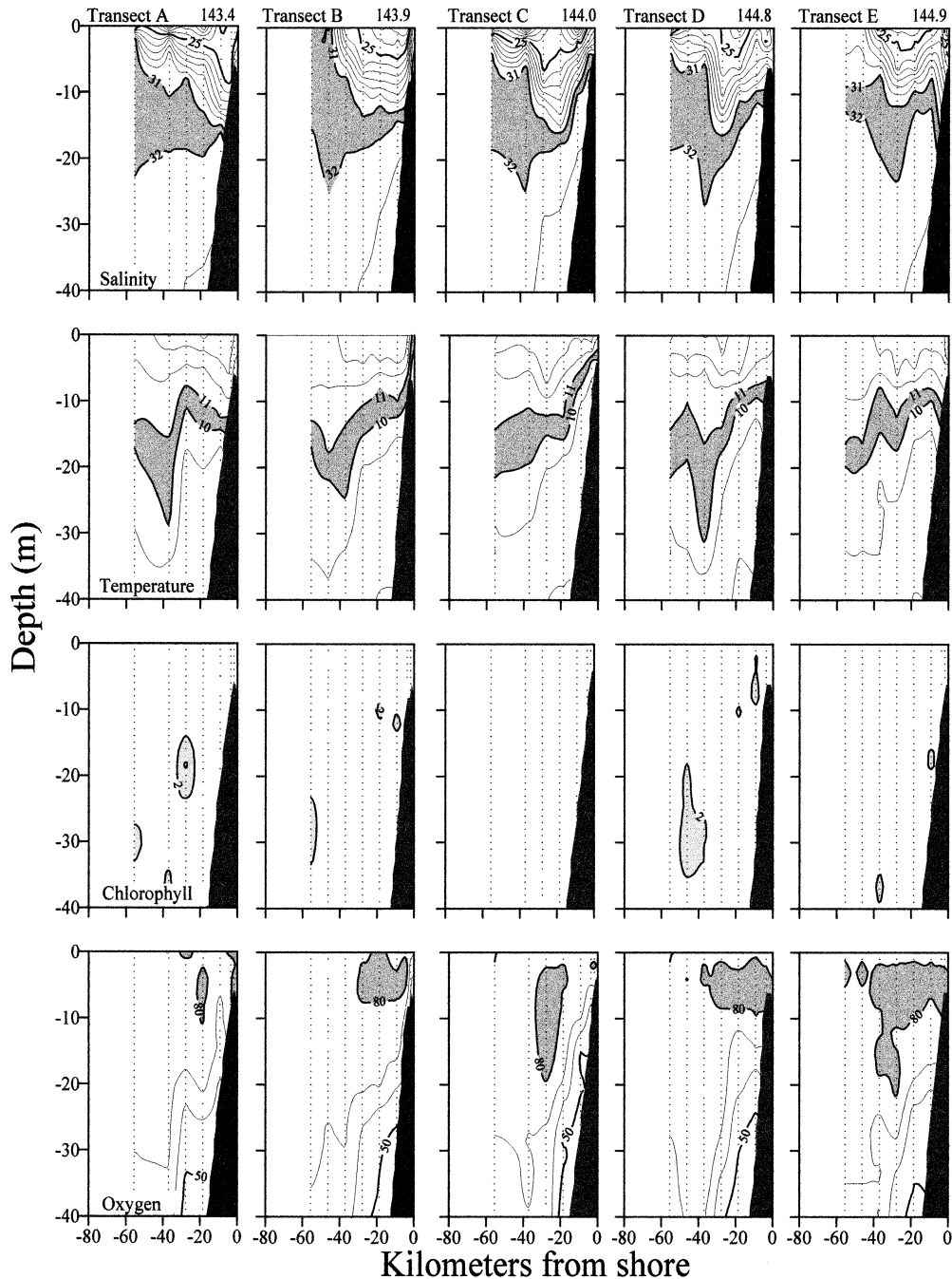


Fig. 3. Cross-shelf transects (A–E) of salinity, temperature, chlorophyll, and percent oxygen saturation during Survey 1. Isohaline intervals are 1 psu, and the regions shaded light gray demark the 31–32 psu water masses. Isotherm intervals are 1°C and the 10–11°C intervals are shaded. Chlorophyll concentrations are contoured into intervals of 2 mg m⁻³. Percent oxygen saturation intervals are 10%, with the ≥80% areas shaded. CTD casts are shown as dotted vertical lines, and the seafloor is shaded dark gray. The number at the top right of each transect is the time (day of year) of the innermost CTD cast.

of the tidal-scale variation in salinity indicates that both coastal and estuarine water masses were routinely advected past the estuarine mooring.

There was also variation on longer time scales. During the period prior to and including Survey 1, salinity time series indicate the presence of Columbia River plume water in the

estuary (Fig. 6A). The low salinity (~22 psu), high temperature (14–16°C), and relatively low fluorescence measured at the estuarine mooring are consistent with the concurrent cruise transect data shown in Fig. 3. During the upwelling/relaxation period encompassing Survey 2, there was a trend of increasing salinity and decreasing temperature in the

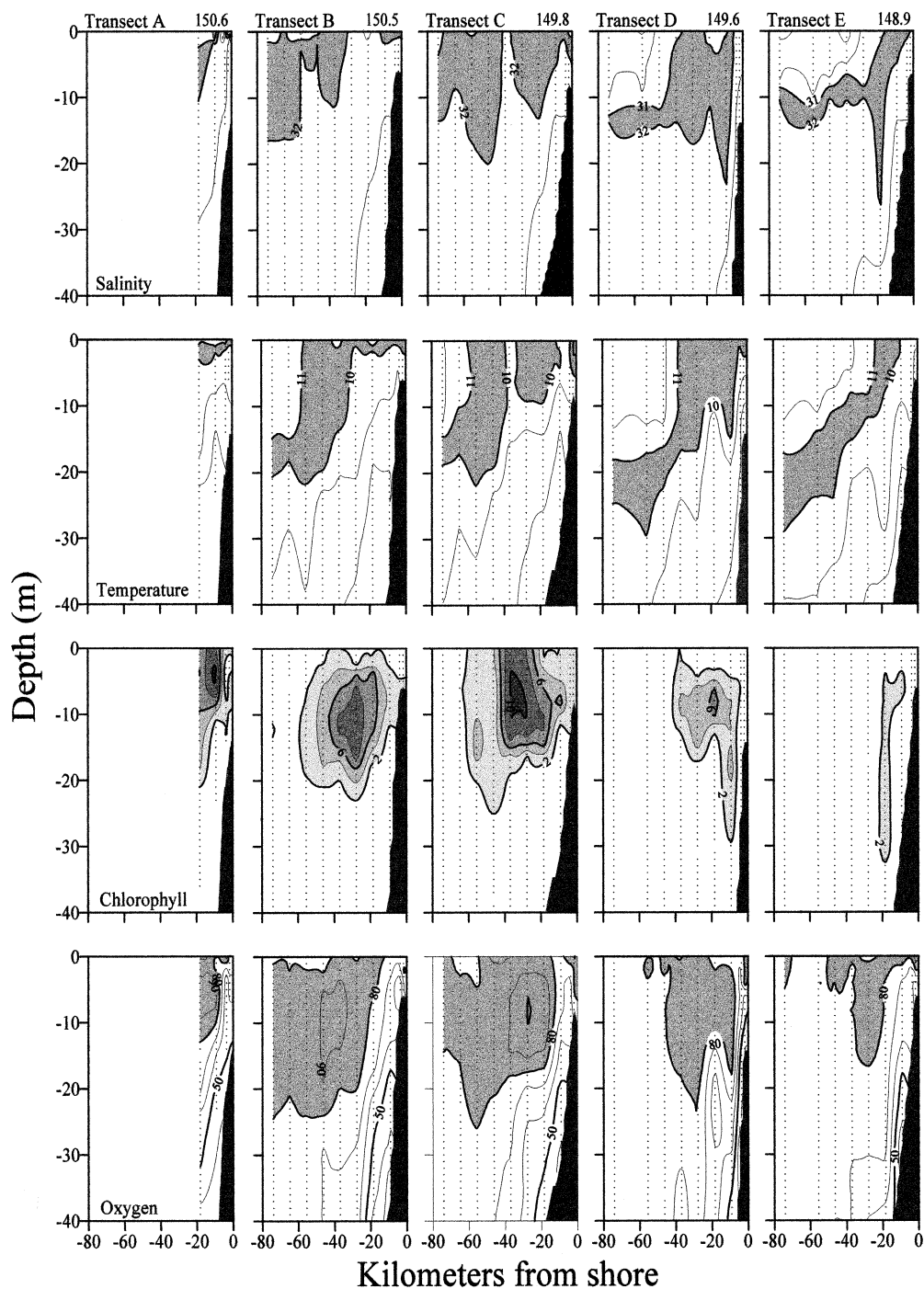


Fig. 4. Cross-shelf transects (A–E) of salinity, temperature, chlorophyll, and percent oxygen saturation during Survey 2. See the legend for Fig. 3.

flood-tide water, but continued low fluorescence (Fig. 6). Maximum salinity (31.3 psu) was reached on DOY 151, indicating the presence of upwelled water at the estuarine mooring site, consistent with the Survey 2 cruise data (Fig. 4). Salinities remained above 30 psu and temperatures below 11°C in the flood-tide water until DOY 151.5, after which there was a decrease in salinity and increase in temperature. This timing is coincident with reduced southward wind

stress (relaxation, Fig. 2) and probably indicates the shoreward movement of the upwelling front.

Synchronously, fluorescence values began increasing in the flood-tide water on about DOY 152 during this relaxation phase, and values peaked 3–4 d later (Fig. 6C). Mean fluorescence during the 25-d measurement period was 7.0 ± 3.5 (SD) units, and maximum fluorescence values were nearly six standard deviations from the mean. Chlorophyll re-

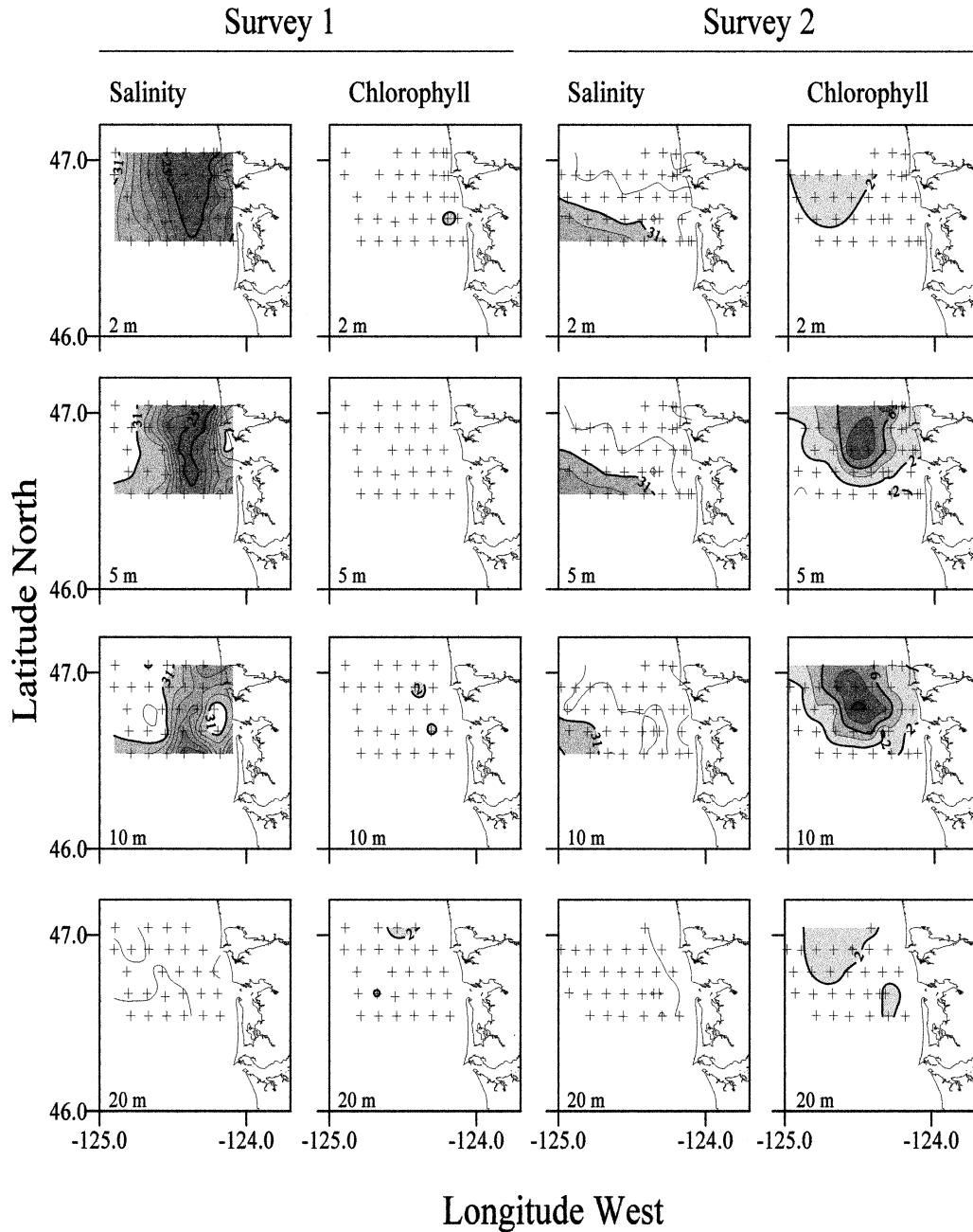


Fig. 5. Surface plots of salinity and chlorophyll during Survey 1 (left two columns) and Survey 2 (right two columns) at each of the indicated depths. Little variation in any water quality constituent occurred below 30 m. Stations are indicated by crosses; shaded sections outside crosses are interpolated data. Isohalines are 1 psu, and shaded areas <31 psu indicate the Columbia River plume. Chlorophyll isopleths are 1 mg m^{-3} .

mained high in the flood-tide water until DOY 157, when salinity abruptly decreased and the tidal signal in the salinity time series was lost (see below). This presumably heralded the return of the Columbia River plume to the coast, which after DOY 161 dominated the estuarine salinity time series. Based on this sequence of water types in the estuary, chlorophyll was low in the plume water, low in the upwelled water, high during relaxation, and variable during the mixing period.

An excerpt from the salinity, fluorescence, and tide time series shown in Fig. 6 demonstrates the influence of tidal advection of nearshore water on the estuarine water properties (Fig. 7). This figure additionally highlights the mixing of bloom and plume water and shows that longitudinal salinity gradients in the estuary reversed in response to the presence of the plume near the estuarine mouth. During the initial plume intrusion, salinity ranged between 20 and 23 psu over a tidal cycle, with higher salinity water entering

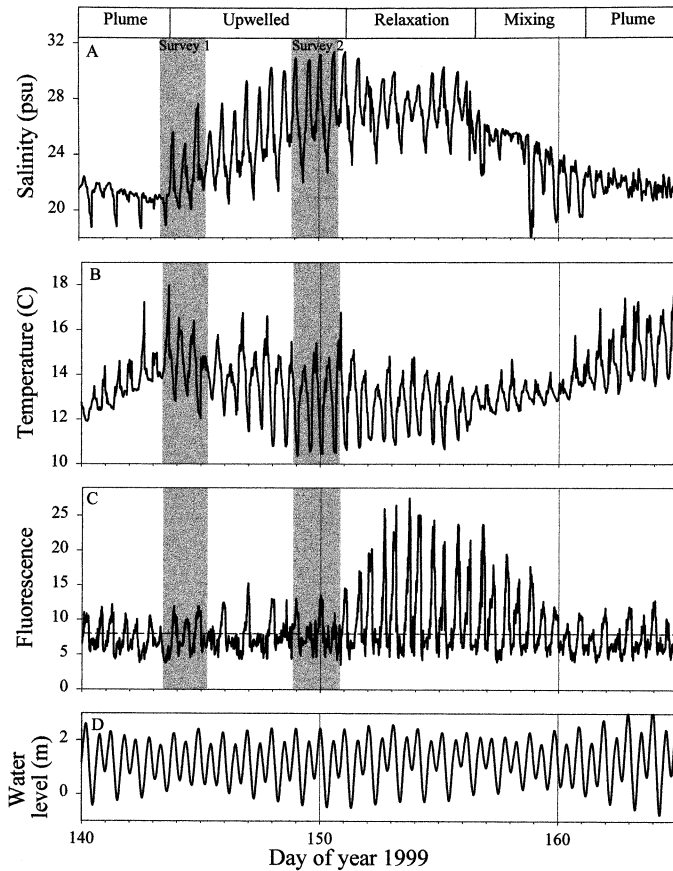


Fig. 6. Time series recorded from the Bay Center and Toke Point estuarine moorings, with the cruise periods indicated by the sections shaded gray. Labels above panel A refer to the inferred origin of water masses entering the estuary. (A) Salinity recorded at Bay Center. (B) Temperature recorded at Bay Center. (C) Fluorescence recorded at Bay Center. The dashed line indicates the 40-d mean fluorescence value. (D) Water level recorded at Toke Point.

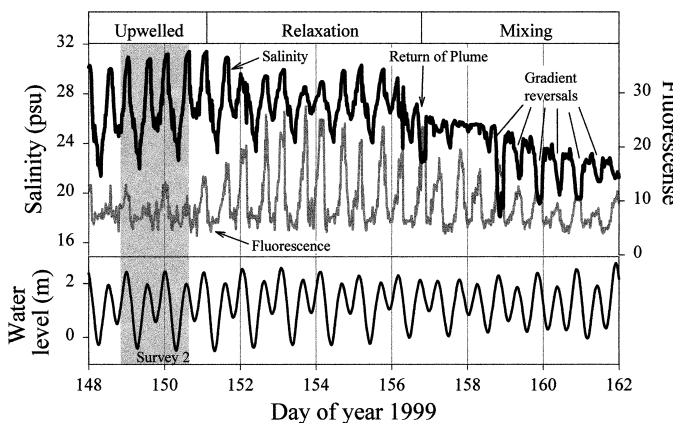


Fig. 7. Time series of salinity, chlorophyll, and water level during the postcruise period indicating bloom and plume intrusions into Willapa Bay.

during flood tide (Fig. 6). As upwelled water was advected into the estuary, salinity ranges increased to a maximum of ~10 psu over a tidal period, and the mooring registered water of both oceanic and estuarine salinities. Fluorescence values during this period were low. However, during the relaxation period, note the close correspondence of the fluorescence, salinity, and tidal height signals (Fig. 7), indicating that chlorophyll entered the estuary with higher salinity water during flood tide. This pattern continued until DOY 157, when the Columbia River plume returned to the estuarine mouth. Subsequently, salinity was lower on flood than ebb tide, indicating the intrusion of the plume by tidal action (Fig. 7). The horizontal salinity gradient was thus reversed from the normal orientation, and higher salinity was present within the estuary than at the mouth. Interestingly, the chlorophyll signal maintained a tidal periodicity during the plume intrusion, suggesting mixing of plume and bloom water in the nearshore zone prior to advection into the estuary.

Discussion

Event scale processes—The role of variation of wind stress on coastal upwelling dynamics and phytoplankton production and on the orientation of the Columbia River plume in the California Current System is well documented (Small and Menzies 1981; Huyer 1983; Hickey 1989). However, the importance of these event-scale processes on estuarine circulation patterns and phytoplankton dynamics in the PNW is only recently being scrutinized. Measurements in Coos Bay, Oregon, were the first to show the intrusion of coastally derived chlorophyll to a PNW estuary (Roegner and Shanks 2001), but these measurements lacked sufficient temporal resolution to ascertain the mechanism controlling the observed chlorophyll variation. The structure and dynamics of the Columbia River plume (Hickey et al. 1998) and its influence on estuarine circulation in Willapa Bay (Hickey et al. in press) have recently been clarified by oceanographic instrument moorings and modeling, but the link to phytoplankton dynamics was not made. The present study benefited from fortuitous timing and is unique in combining detailed and coincident measurements of physical and biological factors from the nearshore oceanic and estuarine systems. These data demonstrate the role of wind forcing on the transport of phytoplankton from its site of production in the nearshore to the estuary. It is likely these processes will prove common where estuaries are adjacent to coasts experiencing coastal upwelling.

Variation in wind forcing—Winds during the observation period exhibited the fluctuating pattern typical of spring in the PNW, alternating between northward, downwelling-favorable and southward, upwelling-favorable conditions and back again (Fig. 2). The transition between states conforms to the 2–10-d period of weather systems in this area (Hermann et al. 1989). Results from our two offshore surveys are consistent with the response of the ocean surface layers with the time-variable alternation of wind (Figs. 3, 4). The *Lady Kaye* cruise was preceded by a period of downwelling-favorable winds, during which time a northward ambient

flow of surface currents, including the Columbia River plume, would be expected (Garcia-Berdeal et al. in press). Survey 1 coincided with the relaxation from a 2-d period of southward winds, but in the surface water, we observed downwelling conditions, low chlorophyll standing stock, and the presence of the Columbia River plume at the coast. At depth, the temperature profiles show evidence of upwelled water approaching the surface during maximum southward wind stress (Fig. 3, Transects B and C), and we surmise the nearshore ocean had insufficient time to completely react to this short period of wind forcing. Following Survey 1 was a more protracted period of upwelling-favorable winds, and although we again sampled during the relaxation phase, the Survey 2 measurements confirmed the presence of upwelled water at the coast. These winds would have generated southward ambient flow and resulted in the displacement of the preexisting plume to the coast off Oregon (Garcia-Berdeal et al. in press). The remnant of the plume in the southwestern portion of the horizontal surface plots of Survey 2 is consistent with the seaward and southward advection of plume waters during upwelling (Fig. 5). The dramatic difference in coastal ocean properties in response to wind variation is testimony to the importance of event-scale processes in this region.

Structure and dynamics of the plume—The spatial structure and temporal dynamics of the Columbia River plume conform to earlier work by Hickey et al. (1998) employing extensive mooring measurements coupled with oceanographic cruises. In the present study, the plume was clearly evident in all Survey 1 transects (Figs. 3, 5). At the surface, the horizontal extent of the plume exceeded 60 km (the furthest we sampled) in all but Transect B, where there was an intense front between 40 and 50 km with a horizontal salinity gradient of ~ 0.5 psu km^{-1} (Fig. 3). Salinity minima were not directly adjacent to the coast but were instead in a shallow lens extending 20 to 40 km from shore (Figs. 3, 5). Plume water penetrated to the bottom in all CTD casts within about 20 km from the coast (except Transect C) and was highly stratified with vertical salinity gradients ranging from 0.6 to 1.4 psu m^{-1} . Maximum thermal stratification ranged from 0.3 to 0.8°C m^{-1} . In contrast, vertical gradients during the upwelling conditions measured in Survey 2 were slight; maximum salinity gradients were only 0.2 psu m^{-1} in the upper 15 m, but most profiles were essentially isohaline (Fig. 4). Similarly, thermal gradients during Survey 2 were $< 0.2^\circ\text{C m}^{-1}$.

Structure and dynamics of the bloom—Both ocean and plume water had chlorophyll concentrations < 2 mg m^{-3} during the Survey 1 transects (Figs. 3, 5). The ocean observations are consistent with downwelling conditions measured in the California Current system, when nutrient-depleted water is present in the photic zone and stratification limits the vertical transfer of nutrients. Low concentrations of chlorophyll are also generally reported in the Columbia River plume, especially under high flow conditions (Stefánsson and Richards 1963; Anderson 1964). Phytoplankton in the turbid Columbia River are often light limited, and the system tends to export particulate matter, including lysed freshwater

algal cells (Lara-Lara et al. 1990). Dissolved nitrate and phosphate are apparently utilized rapidly at the plume margins as river water mixes in the nearshore zone (Conomos et al. 1972; Klinkhammer et al. 1997), and production might also be stimulated by entrainment of nutrient-rich bottom water into the plume (Stefánsson and Richards 1963). However, we did not observe enhanced chlorophyll concentrations at the plume boundaries during our surveys.

In contrast, ocean productivity in the region is greatly enhanced during upwelling when limiting nutrients are supplied to the photic zone. The Survey 2 transects that occurred 4 d after the onset of strong equatorward wind stress illustrate the event-scale variation in phytoplankton production. The horizontal distribution of the bloom conforms to the advective patterns displayed by the salinity isopleths discussed above. Chlorophyll was distinctly lower near the coast, and bloom material was generally not adjacent to the mouths of Grays Harbor or Willapa Bay. These results are in general agreement with measurements of active upwelling off the Oregon coast, where maximum chlorophyll concentrations were usually seaward of the upwelling front and arranged in alongshore bands that followed bottom topography (Small and Menzies 1981). The patterns of salinity and chlorophyll are likely caused by seaward advection of upwelled water and nutrients combined with the generation time of the phytoplankton seed stock.

Estuarine dynamics—The time series of physical oceanographic parameters measured at the Bay Center estuarine mooring site clearly show the influence of tidal and event-scale processes on estuarine dynamics. The high-frequency variation at the estuarine mooring site was controlled mainly by tidal advection. Comparisons of the power spectra of salinity, temperature, and fluorescence with water level indicate synchronous peaks in frequency at the 12.4 h M_2 tidal constituent and multiples. On longer time scales, estuarine water properties were controlled primarily by wind-forced processes that advected water to the estuarine mouth and affected gravitational circulation patterns. The lag between wind stress and temperature and salinity values in Willapa Bay is 1–2.5 d and is due to the progression of a gravity current up the estuary (Hickey et al. in press). Inflow is driven by the ocean–estuary pressure difference that is modified each time the ocean density changes. The estuarine mooring recorded two Columbia River plume intrusions separated by an intrusion of dense upwelled water (Fig. 6). These plume intrusions are a common phenomenon for Willapa Bay (Hickey et al. in press), and probably Grays Harbor and other coastal estuaries north of the river mouth, but are expected to be more episodic in Oregon estuaries, especially with increasing distance south of the Columbia River. The frequency and magnitude of plume intrusions constitutes a fundamental difference between Washington and Oregon coastal estuaries.

The coherence between time series of salinity, fluorescence, and sea level indicates that the high fluorescence observed in the estuary had a coastal origin (Figs. 6, 7). During the period when upwelled coastal water entered the estuary, maximum sea level, salinity, and fluorescence were synchronous. This is consistent with lateral advection on flooding

tides. Conversely, during the period when low-salinity Columbia plume water entered the estuary, maximum sea level was associated with high fluorescence but with low salinity, again consistent with a coastal origin. During this period, residual chlorophyll from the upwelling-generated bloom had likely mixed with the plume water as it traveled along the coast. These observations correlate well with the series of tidal-scale measurements made earlier in Coos Bay (Roegner and Shanks 2001): The variation in chlorophyll abundance noted in the intensive, 24-h “snapshots” from Coos Bay conform to portions of the event-scale upwelling–relaxation cycle we measured in Willapa Bay, albeit without the presence of the Columbia River plume.

Relation to other studies—Few studies of estuarine phytoplankton dynamics have demonstrated large-scale importation of coastal phytoplankton to an estuarine system. Examples of this estuarine–nearshore link include Coos Bay, Oregon (Roegner and Shanks 2001); North Inlet, North Carolina (Dame et al. 1991); and Peel Inlet, Western Australia (Black et al. 1981). More common are investigations demonstrating estuarine phytoplankton production that is stimulated by advection of nutrients from ocean to estuary. Notable are studies of the Galician Rías Baixas of Northwest Spain (e.g., Alvarez-Salgado et al. 1996; Nogueira et al. 1997). In these systems, autochthonous blooms are supported during wind relaxation events when ocean-derived nutrients, previously imported during upwelling, are maintained in the estuarine photic zone. Similarly, relaxation following upwelling can promote phytoplankton growth in coastal embayments by delivering nutrients to nearshore areas (Lara-Lara et al. 1980; Bailey and Chapman 1991). Both Willapa Bay and Coos Bay also receive newly upwelled water that is expected to be high in dissolved nutrients, and we surmise the relatively rapid flushing of the marine-dominated section of these PNW systems might limit the formation of autochthonous blooms (Monet 1992). However, more work is needed to confirm this and evaluate the cycling of ocean-derived nutrients into estuarine water column and benthic microflora or seagrass biomass.

Consequences of chlorophyll intrusions to estuarine fauna—In this study, we demonstrated that significant variation in chlorophyll and physical parameters occur on both tidal and event time scales in Willapa Bay. What is the consequence of the ocean- versus land-derived forcing of phytoplankton supply to sedentary suspension-feeding organisms that rely on the advection of seston for their food supply? On the estuarine spatial scale, individual animals within a habitat continuum might experience very different time-integrated food levels, depending on proximity to the phytoplankton source, intertidal versus subtidal exposure that affects feeding times, and mechanisms of advective transport, including the degree of vertical mixing and resuspension. Additionally, the prodigious filtering abilities of bivalves can have a negative feedback on mean growth rates through progressive resource depletion (Cloern 1982; Officer et al. 1982). Animals farther downstream of the phytoplankton source potentially receive lower quality or quantity of food, resulting in diminished growth compared to animals farther

upstream (Muschenheim and Newell 1992). Ancillary evidence from Willapa Bay indicates food resources do vary on the estuary spatial scale: Depth-integrated chlorophyll concentrations decrease with distance from the estuarine mouth (Newton et al. 2000), and trends of oyster production follow a complimentary spatial pattern (Schoener and Tuffs 1987). We hypothesize bloom intrusions are responsible in part for these observed gradients in phytoplankton biomass and oyster growth. Present studies are aimed at clarifying the role of benthic–pelagic coupling between suspension feeders and ocean-derived chlorophyll in PNW estuaries.

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