

Climatic and Tidal Forcing of Hydrography and Chlorophyll Concentrations in the Columbia River Estuary

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Abstract Hydrographic patterns and chlorophyll concentrations in the Columbia River estuary were compared for spring and summer periods during 2004 through 2006. Riverine and oceanic sources of chlorophyll were evaluated at stations along a 27-km along-estuary transect in relation to time series of wind stress, river flow, and tidal stage. Patterns of chlorophyll concentration varied between seasons and years. In spring, the chlorophyll distribution was dominated by high concentrations from freshwater sources. Periods of increased stream flow limited riverine chlorophyll production. In summer, conversely, upwelling winds induced input of high-salinity water from the ocean to the estuary, and this water was often associated with relatively high chlorophyll concentrations. The frequency, duration, and intensity of upwelling events varied both seasonally and interannually, and this variation affected the timing and magnitude of coastally derived material imported to the estuary. The main source of chlorophyll thus varied from riverine in spring to coastal in summer. In both spring and summer seasons and among years, modulation of the spring/neap tidal cycle determined stratification, patterns of mixing, and the fate of (especially freshwater) phytoplankton. Spring tides had higher mixing and neap tides greater stratification, which affected the vertical distribution of chlorophyll. The Columbia River

differs from the more tidally dominated coastal estuaries in the Pacific Northwest by its large riverine phytoplankton production and transfer of this biogenic material to the estuary and coastal ocean. However, all Pacific Northwest coastal estuaries investigated to date have exhibited advection of coastally derived chlorophyll during the upwelling season. This constitutes a fundamental difference between Pacific Northwest estuaries and systems not bounded by a coastal upwelling zone.

Keywords Chlorophyll concentration · Hydrography · Upwelling · Columbia River estuary · Northeast Pacific

Introduction

The Columbia River estuary is the interface between a high-volume river and a wind-forced coastal upwelling zone. River and ocean end members exhibit significant variability in forcing functions that influence estuarine circulation (Bruland et al. 2008; Chawla et al. 2008). The fluvial end member varies seasonally and interannually in the timing and magnitude of volume flux, with maximum flows during the spring freshet in May or June and a relatively large interannual variation in total flow caused by runoff of winter snow pack (Mote et al. 2003). Flow patterns are further modified by operation of Columbia River dams and flood control structures.

The ocean end member is influenced by coastal wind stress that forces upwelling and downwelling conditions on the shelf and nearshore zone (Huyer 1983; Hickey 1989). Wind stress controls variability in cross-shelf gradients of biophysical properties and the water masses present at the estuary mouth (Roegner et al. 2002; Dale et al. 2008). Large variation in the direction, duration, and intensity of

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coastal wind stress occurs over seasonal and interannual timescales. Estuarine circulation is further forced by spring/neap variation in the mixed semidiurnal tides (amplitudes between 1.0 and 3.5 m), which modulate stratification and mixing processes (Jay and Smith 1990; Chawla et al. 2008). During spring tides, increased tidal mixing favors salt wedge formation with intermediate tidal intrusion length, while neap tides foster stratification and increased salinity penetration into the estuary. These baroclinic and barotropic forces generate dynamic circulation patterns with horizontal currents of 1 to 2 ms⁻¹ and a hydrologic residence time from one to several days (Jay and Smith 1990).

In turn, these factors affect advection of phytoplankton and biogeophysical cycling in the Columbia River estuary. Previous studies have focused mainly on the riverine end member of the system, which has been shown to be a significant source of phytoplankton to the estuary. Freshwater diatoms dominate most riverine samples, and the species composition resembles that of eutrophic lakes (Haertel et al. 1969; Prahl et al. 1998). Chlorophyll concentrations are large and maximal during the spring diatom bloom and typically range between 15 and 30 mg m⁻³ (Prahl et al. 1998; Sullivan et al. 2001). Concentrations during summer are reduced to 5 to 10 mgm⁻³ and reach minimal levels in winter. Nutrients (N, P, and Si) rarely became limiting to phytoplankton production in the river due to numerous point sources of nutrient addition coupled with short residence times of water masses (Prahl et al. 1998; Sullivan et al. 2001; Bruland et al. 2008). Along the tidal fluvial section (about 230 rkm from Bonneville Dam to the estuary), chlorophyll concentrations tend to increase with distance downstream as the standing stock of phytoplankton accumulates (Small et al. 1990). However, these freshwater cells lyse on contact with 3–5-psu salinity water (Lara-Lara et al. 1990), and much of the organic material entering the estuary may be biologically processed in estuarine turbidity maxima (ETM) (Baross et al. 1994; Prahl et al. 1997; Small and Prahl 2004). During moderate- and high-flow conditions, the system tends to export nutrients and particulate organic matter via the Columbia River plume (Klinkhammer et al. 1997; Bruland et al. 2008). During low-flow conditions that typify summer conditions, salinity intrusion and residence times are maximized and ocean-derived nutrients and phytoplankton can be advected to the estuary (Haertel et al. 1969; Lara-Lara et al. 1990).

The effect of variation in wind stress on the ocean end member and on hydrographic properties of the Columbia River estuary has received less attention than the river end member. Phytoplankton production on the Oregon continental shelf is dependent on light intensity and wind-forced upwelling of subsurface nutrients (Huyer 1983; Hickey 1989; Henson and Thomas 2007). Upwelled water is colder (<10°C), saltier (>31 psu), and higher in nitrate

(>30 μmolL⁻¹) than surface water and, when upwelled into the photic zone, stimulates phytoplankton growth. Winds become favorable for upwelling after a seasonal switch in atmospheric pressure regimes known as the “spring transition” (Huyer et al. 1979). Timing of the spring transition varies between March and July, and this has major implications for ocean ecology, as early spring transitions generally presage good ocean conditions for the coastal food chain (Peterson and Keister 2003; Kosro et al. 2006; Barth et al. 2007) and fisheries (Logerwell et al. 2003; Shanks and Roegner 2007). Upwelling is a dynamic process that is highly sensitive to the frequency, intensity, and duration of wind events (Austin and Barth 2002), which in turn are driven by the position and propagation of atmospheric pressure systems (Strub et al. 1987; Henson and Thomas 2007). Winds during the March through October upwelling season often oscillate between upwelling and downwelling or relaxation conditions at 2 to 6 day weather and 20-day intraseasonal periods, resulting in pulses of productivity in the coastal ocean (Bane et al. 2005). A rapid shoreward movement of the surface mixed layer and the phytoplankton it contains can follow relaxation from upwelling winds (Roegner et al. 2002; Dale et al. 2008).

The present study expands previous investigations in the river-dominated Columbia River estuary. We examine the response of estuarine hydrographic parameters to varied climatic forcing during spring and summer 2004 to 2006, and we focus on the role of local wind stress on the distribution of chlorophyll within the estuary. Our observations confirm the riverine source of chlorophyll during the spring phytoplankton bloom, as well as the role of river flow on modulating the magnitude of freshwater phytoplankton transport. We further show that the vertical distribution of riverine chlorophyll is sensitive to the spring/neap tidal modulation. On a seasonal scale, we demonstrate that wind-induced upwelling controls the advection of high salinity and coastally derived chlorophyll to the estuary. On an interannual scale, we conclude that the magnitude, origin, and spatial distribution of chlorophyll in the estuary are largely controlled by climatic variation in both river flow and coastal wind stress.

Materials and Methods

Time Series Measurements

Variation in climatic forcing affecting estuarine hydrography was assessed with time series of river flow, coastal wind stress, and maximum daily estuarine salinity. Time series were compiled for March through September of 2004 to 2006. Daily river flow (Q , m³s⁻¹) and temperature were recorded at Bonneville Dam (rkm 234; <http://www.cbr.washington.edu>).

To explore interannual and seasonal variation in river forcing and river temperature, we compared scatterplots of anomalies from the 10-year mean daily temperature and flow at Bonneville Dam each year from March through September.

Coastal wind velocity vectors were measured at NOAA buoy 46029 (46.12° N, 124.51° W) or when necessary to bridge data gaps from NOAA buoy 46041 (47.34° N, 124.75° W) (www.ndbc.noaa.gov). Hourly wind vectors were converted to mean daily alongshore wind stress (τ_N , Nm^{-2}). Positive (northward) wind stress induces downwelling, and negative (southward) wind stress drives upwelling. We computed a time series of cumulative daily northward wind stress ($\Sigma\tau_N$) from March through September to compare the relative timing and magnitude of the net upwelling and downwelling periods between years. Within the estuary, we used the tidal daily maximum salinity (S_{max} , psu) recorded at CORIE station Red 26 (rkm 7.5; 46.21° N, 123.95° W) as a measure of oceanic input (www.ccalmr.org.edu/CORIE). Linear regression with nearby stations was used to fill data gaps when necessary. Time series of these variables were constructed for each of the 3 years to examine seasonal and interannual variations in climatic forcing. We used cross-correlation to discern the effect of mean daily northward wind stress on detrended maximum daily estuarine salinity (at lags -7 to 0 day). Spectral analysis was used to assess possible spring/neap tidal signals in the salinity time series, enabling a 2-day resolution.

For interannual comparisons of the frequency, duration, and intensity of wind events, we identified individual upwelling and downwelling weather patterns and periods of low wind stress (LWS) (calm periods) from low-pass-filtered wind stress time series (3-day running average). We based identifications on a wind stress threshold τ_N of $\pm 0.03 \text{ Nm}^{-2}$, which has been observed to instigate changes in sea surface temperature values at Pacific Northwest (PNW) coastal sites (Roegner et al. 2007). Upwelling events were defined as periods of at least 3 days of consecutive $\tau_N \leq -0.03 \text{ Nm}^{-2}$, downwelling events as $\tau_N \geq 0.03 \text{ Nm}^{-2}$, and periods of LWS between $\pm 0.03 \text{ Nm}^{-2}$. We determined the number, duration, and total stress of upwelling and downwelling periods and the duration of LWS periods, for the March through September period of each year.

Water Property Measurements

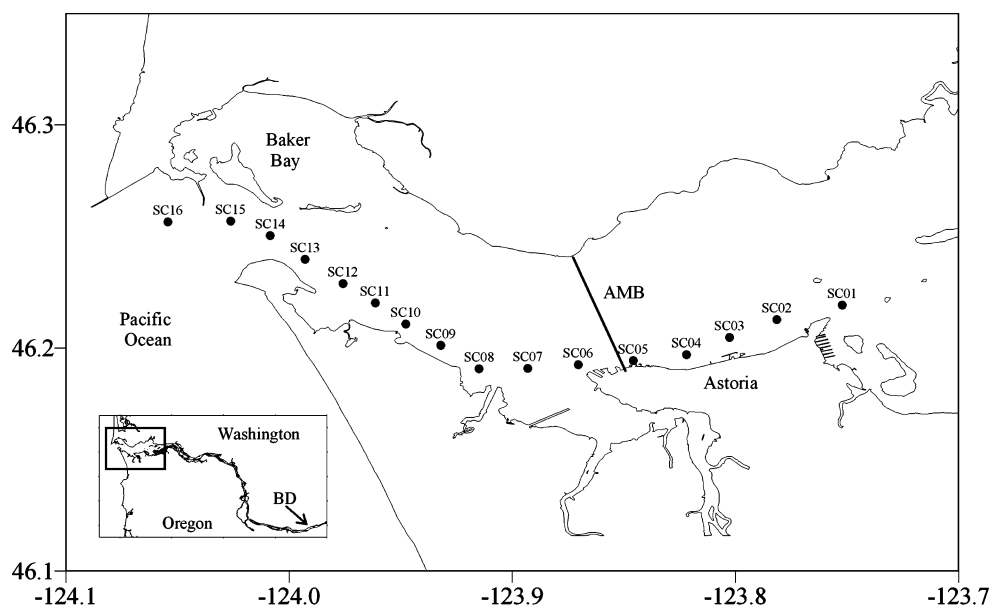
Hydrographic surveys were conducted at 16 stations along a 27-km transect of the Columbia River South Channel (shipping lane) extending from Tongue Point (rkm 27) to Navigation Buoy 10 (rkm 0) (Fig. 1). Stations SC16 and SC15 were only sampled when conditions on the bar permitted. At each station, vertical profiles of water properties were made with a Seabird 19 plus CTD equipped

with a Wet Labs WET star fluorometer. Fluorometric readings were converted to chlorophyll *a* concentrations using factory calibrations and should be considered estimates. In 2004, cruises occurred during spring and neap tidal conditions in April (three cruises) and August (three cruises). In 2005, we sampled once each in March and April and twice each in June and August. During 2006, we sampled monthly except during September, when two cruises were conducted. As a consequence, surveys were clustered in March–April, June, and August–September. Twenty-one cruises were used in the analyses outlined below. Of these, we present four transects that illustrate spring and neap patterns during the spring phytoplankton bloom and during the summer upwelling period. Surveys were semi-synoptic and required 2 to 4 h to complete, depending on surface current velocity. For all surveys, standard temperature–salinity (T/S) diagrams were constructed to evaluate end member water masses and mixing processes. Analogously, chlorophyll–salinity (C/S) diagrams were made to appraise the source of chlorophyll to the estuary. We used linear regression of T/S and C/S diagrams to evaluate mixing processes in the estuary (Roegner and Shanks 2001; Bruland et al. 2008). Negative slopes indicate higher temperatures or chlorophyll values in the river end member than the ocean end member and positive slopes the converse.

Indices of Biophysical Parameters

Chlorophyll and physical variables were transformed into indices to investigate the influence of climatic and tidal forcing on regulating chlorophyll delivery to the Columbia River estuary. Salinity was used to delimit the ocean and river end members of the estuarine continuum. The freshwater source was designated by salinity ≤ 4 psu, and the ocean source was assigned to salinity ≥ 29 psu. These values encompass some mixing of end members within the estuary. For each cruise, the mean chlorophyll concentration was calculated for all bins within these salinity ranges. This produced paired variables for each date sampled: chlorophyll in ocean water (COW) and chlorophyll in river water (CRW). We then created a source ratio (SR) = CRW/COW, where $\text{SR} > 1$ indicates chlorophyll enrichment in river water and $\text{SR} < 1$ the converse. From the river flow data, we created a cumulative stream flow index (SF) as the mean of the mean daily river flow at Bonneville Dam for the previous 4 days. This time frame accounts for advection of chlorophyll downstream and into the estuary. Flow conditions were categorized based on the 10-year historical data from Bonneville Dam as “low” ($< 4,000 \text{ m}^3 \text{ s}^{-1}$), “medium” ($4,000 \leq \text{SF} \leq 8,000 \text{ m}^3 \text{ s}^{-1}$), and “high” ($> 8,000 \text{ m}^3 \text{ s}^{-1}$). We used the 4-day cumulative northward wind stress (CWS, Nm^{-2}) as an index of forcing from

Fig. 1 Columbia River estuary sample stations in the South Channel. *AMB* Astoria–Megler Bridge. Instruments at Station R26 are located near SC09. *Inset* shows regional location. *BD* Bonneville Dam



upwelling/downwelling winds. CWS, which could have positive or negative values, was created by summing the mean daily northward wind stress for the previous 4 days to account for “spin up” of wind stress on ocean conditions. CWS was categorized as “weak” ($|CWS| < 0.2$), “moderate” ($0.2 \geq |CWS| \leq 0.4$), or “strong” ($|CWS| > 0.4$) upwelling/downwelling conditions. Finally, we used lunar stage to index the spring/neap cycle (SN, dimensionless). Values ranged from 0 (new moon, spring tide) to 1 (full moon, spring tide), with 0.5 denoting neap periods. We then plotted \log_{10} SR against day of year (DoY), SF, CWS, and SN to examine time and each physical forcing on advection of chlorophyll to the estuary. We also plotted CRW by COW to look for seasonal changes in chlorophyll intensification. Principal components analysis was used to evaluate the relative variance explained by these indices. Finally, we determined the date of the spring transition to upwelling conditions based on sea-level records as in Shanks and Roegner (2007) and created a time index (DoT) where the date of the transition for a particular year was normalized to zero, and days sampled before that date were negative and those after were positive. We then regressed \log_{10} SR by DoT to estimate the time response of chlorophyll in the estuary to the spring transition.

Results

Time Series of Physical Data

Inspection of the time series of instrument data from riverine, estuarine, and oceanic stations revealed significant variation in climatic conditions within and between years

(Figs. 2, 3, 4, and 5). Based on the temperature and flow anomalies, 2004 was a warm, low-flow year (Figs. 2 and 3). Q remained around $4,000 \text{ m}^3 \text{ s}^{-1}$ from March through mid-April and then increased steadily to a brief maximum of $\sim 8,000 \text{ m}^3 \text{ s}^{-1}$ around 1 June. Between June and July, flow decreased from this peak and returned to and fluctuated around $4,000 \text{ m}^3 \text{ s}^{-1}$ from late July through August before further decreasing to low levels after early September. The year 2005 was a low-flow year with Q well below average during spring and slightly below average in summer and temperatures generally warmer than the 10-year average (Figs. 2 and 4). Q remained near $4,000 \text{ m}^3 \text{ s}^{-1}$ until early May and increased to a maximum of about $8,000 \text{ m}^3 \text{ s}^{-1}$ in mid-May. Flow decreased and remained between $5,000$ and $6,000 \text{ m}^3 \text{ s}^{-1}$ until 1 August and then dropped below $4,000 \text{ m}^3 \text{ s}^{-1}$. In contrast, 2006 had high flow during spring and slightly below average flow in summer, with more evenly distributed temperature deviations during both periods (Figs. 2 and 5). Stream flow increased rapidly from $5,000$ to $9,000 \text{ m}^3 \text{ s}^{-1}$ in early April and remained above $8,000 \text{ m}^3 \text{ s}^{-1}$ through the end of June. Peak flow was $\sim 11,000 \text{ m}^3 \text{ s}^{-1}$. Flow steadily decreased throughout June and remained at or below $4,000 \text{ m}^3 \text{ s}^{-1}$ after early August.

Based on low-pass-filtered wind stress time series and the critical threshold $\tau_w = 0.03 \text{ Nm}^{-2}$, the onset, frequency, duration, and intensity of wind events varied between years (Figs. 3, 4, and 5; Table 1). The year 2004 was characterized by fairly periodic alternating upwelling and downwelling periods of average intensity (Fig. 3). Cumulative wind stress remained close to zero throughout the sample period and became negative (upwelling-dominant) around 1 July. March through April 2004 was a period of varying wind cycles, followed by an extended period of

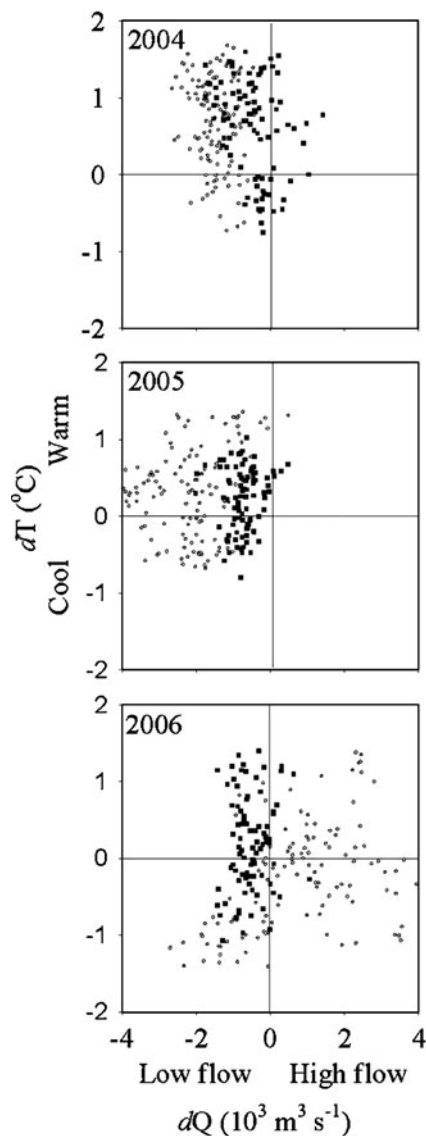


Fig. 2 Scatterplot of temperature versus stream flow deviations from the 10-year mean daily values recorded at Bonneville Dam. Spring (*gray*) and summer (*black*) periods are distinguished

low wind stress in May. The remainder of the measurement period through mid-September was categorized by moderate upwelling conditions punctuated by reversals to downwelling periods. We identified nine upwelling events totaling 70 days, with four downwelling events totaling 29 days, and 115 days of low wind stress, including the nearly continuous period from May to mid-June. The year 2004 had the lowest total northward wind stresses and most numerous days of LWS of the study.

The 2005 study period was dominated by downwelling winds or low wind stress from March through June and delayed but strong upwelling thereafter (Fig. 4). Cumulative wind stress remained constant and positive from April until commencement of upwelling and declined steadily

during the summer upwelling period; however, it did not reach zero until mid-September. There were four upwelling events that summed to 68 days, four downwelling events totaling 55 days, and low wind stress of 91 days (including week-long periods in April–May and June). The total number of upwelling days, total upwelling intensity, and total days of downwelling plus low wind stress were similar in 2004 and 2005; however, the timing and periodicity of wind events were very different (Table 1).

In contrast, 2006 was a year of strong upwelling (Fig. 5). Wind stress turned negative in mid-April and remained in upwelling mode throughout the measurement period except for three low- to moderate-intensity downwelling events. Cumulative wind stress was high and positive during much of the spring and turned negative at the beginning of August. There were five upwelling events lasting 117 days with a total intensity twice that of 2004 or 2005 (Table 1). There were six downwelling events of moderate total intensity extending for 58 days (similar to 2005) and only 39 days of low wind stress.

Seasonal wind stress patterns influenced trends in maximum estuarine salinity and the intrusion of high-salinity water into the estuary. In general, S_{\max} values remained below 31 psu during spring downwelling conditions and increased coincident with upwelling intensity. In 2004, intrusions of high-salinity water were first detected in June and repeated incursions were in phase with upwelling pulses (Fig. 3). There were 22 of 212 days (10.4%) where $S_{\max} \geq 31$ psu. In 2005, maximum estuarine salinity was depressed until the end of June and increased and remained above 31 psu for 56 of 186 days (30.1%) during the long summer period of persistent upwelling (Fig. 4). In 2006, high-salinity water first entered the estuary following the first main upwelling period in mid-May (Fig. 5). Salinity declined sharply during periods of sustained downwelling of moderate intensity and high flows in May and July and otherwise oscillated around 31 psu for the remainder of the measurement period. There were 50 of 131 days (38.2%) where $S_{\max} \geq 31$ psu, but equipment failure in late summer precluded a full accounting.

In all years, maximum daily estuarine salinity was correlated with event-scale variation in wind stress (Figs. 3, 4, and 5). S_{\max} increased with upwelling winds and declined sharply during downwelling events, especially during periods of high stream flow. However, note that, with the appropriate upwelling wind stress, high salinity could enter the estuary even under high-flow conditions, likely through a combination of baroclinic and barotropic forcings (Hickey et al. 2002). For all years, there were significant negative correlations between northward wind stress and maximum daily estuarine salinity at -3 - to -1 -day lags for the 1 March to 30 September period (Table 2). Correlations improved when the period 15 June to 30 September was considered.

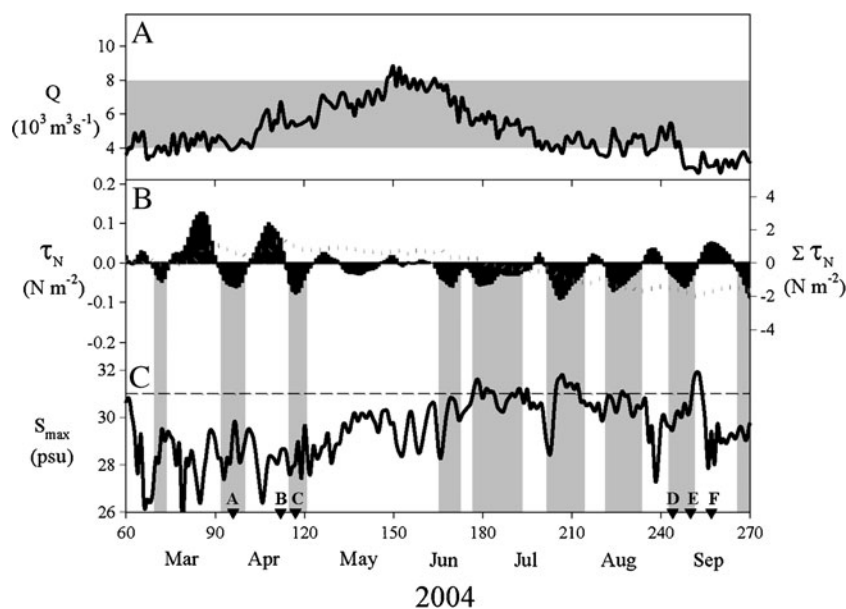


Fig. 3 Time series of physical drivers and maximum estuarine salinity March–September 2004. *A* Mean daily river discharge from Bonneville Dam (Q , $\text{m}^3 \text{s}^{-1}$). *Gray band* designates the “medium”-flow regime. *B Bars*: low-pass-filtered mean daily northward wind stress (τ_N , N m^{-2}). *Gray-shaded sections* denote upwelling events defined as ≥ 3 days of

consecutive $\tau_N < -0.03$. *Dotted line and right y-axis*: cumulative τ_N . *C* Maximum daily estuarine salinity (S_{max} , psu). *Dashed line* indicates 31 psu threshold for oceanic water. *Triangles on bottommost x-axis* indicate timing of hydrographic cruises; letters correspond to plots in Fig. 7 and Table 3

There was thus a rapid response of S_{max} to coastal wind stress, with increasing S_{max} during upwelling periods and rapid decreases in S_{max} during wind reversals.

Water Column Structure and Chlorophyll Distribution

Spring/neap tidal modulation controlled the vertical structure of the water column and influenced the distribution of chlorophyll. During spring tides, salinity intrusion occurred as a salt

wedge characterized by strong horizontal and moderate vertical salinity gradients (Fig. 6a). During neap tides, the estuarine water column stratified, with minimal horizontal and intense vertical salinity gradients (up to 5 psu^{-1} in the halocline; Fig. 6b). The chlorophyll distribution followed a strong seasonal trend. In spring, the chlorophyll concentration could be highly enriched in river water. When salt wedge conditions occurred, the chlorophyll distribution was vertically mixed and concentrations generally declined from the riverine source

Fig. 4 Time series of physical drivers and maximum estuarine salinity March–September 2005. See Fig. 3 legend

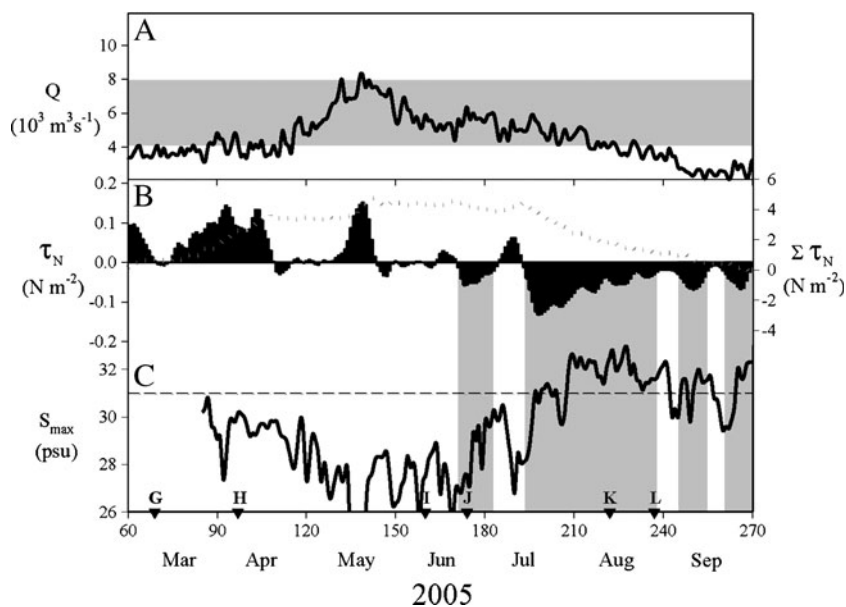
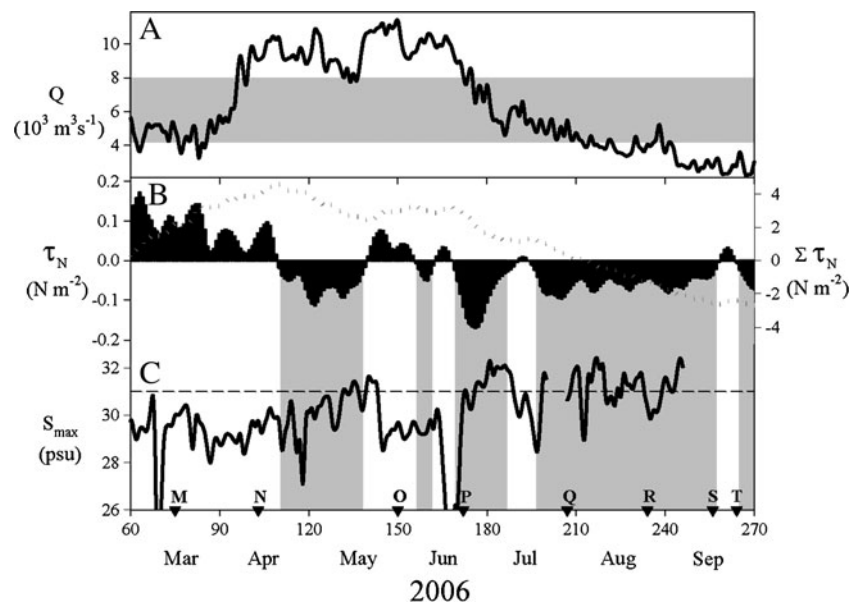


Fig. 5 Time series of physical drivers and maximum estuarine salinity March–September 2006. See Fig. 3 legend



to the ocean end member (Fig. 6a). During neap tide stratification, fluvial conditions could extend to the river mouth even at slack high water, and chlorophyll enrichment was largely isolated in the low-salinity surface water (Fig. 6b). The estuary thus progressed through a neap-to-spring cycle of stratification–destratification, with the riverine-derived chlorophyll phasing through vertically mixed to surface-concentrated regimes. The tidally forced spring/neap variation in salinity structure was strengthened during the summer upwelling period, with higher temperature and salinity gradients (Fig. 6c, d). However, chlorophyll concentrations were more spatially variable during summer and were often enriched in intruding high-salinity water rather than river water, indicating a coastal origin (discussed below).

T/S and C/S Diagrams

During hydrographic surveys, salinity ranged from riverine to oceanic except during cruises in April 2004 and May 2006, when little saltwater was present (Fig. 7). The linear temperature–salinity relationship in all T/S plots indicated that conservative mixing of ocean and river end members occurred along the estuarine horizontal scale (although vertical stratification could be extreme). Regression slopes were generally positive in early spring and negative after

May, with a good fit of regression lines to the data (Table 3). In spring, the temperature of river and ocean water was similar. As summer progressed, temperature steadily increased in the river water: maximum thermal variation occurred in late summer when cold upwelled water mixed with warm river water in the estuary. High-salinity water ≥ 31 psu (dashed vertical line on the T/S diagrams) was generally confined to summer samples after the onset of upwelling-favorable winds.

C/S diagrams reveal a complex pattern of chlorophyll distribution in the estuary (Fig. 7). During spring 2004 and 2005, high chlorophyll concentrations (up to 40 mg m^{-3}) were present in river water, and concentrations decreased with increasing salinity. In 2006, spring samples exhibited reduced and more variable concentrations of chlorophyll in river water (5 to 20 mg m^{-3}). These patterns are consistent with freshwater diatom blooms being transported into the estuary (Haertel et al. 1969; Prah1 et al. 1998), where they lyse in contact with salt water (Lara-Lara et al. 1990). The year 2006 was a high-flow year, which may have limited the accumulation of diatom cells in river water relative to the moderate-flow conditions during 2004 and 2005. After June, riverine chlorophyll levels were generally $<6 \text{ mg m}^{-3}$, and the incidence of salinity >31 psu increased. This high-salinity water often contained enhanced chlorophyll con-

Table 1 Frequency, duration, and intensity ($\Sigma\tau$, Nm^{-2}) of wind events during March through September, 2004–2006

Year	Upwelling				Downwelling				LWS	
	Events	Days	%	$\Sigma\tau$	Events	Days	%	$\Sigma\tau$	Days	%
2004	9	70	32.7	-3.8	4	29	13.6	2.0	115	53.7
2005	4	68	31.8	-4.3	4	55	25.7	4.7	91	42.5
2006	5	117	54.7	-8.1	6	58	27.1	4.8	39	18.2

LWS low wind stress, % percent of measurement period

Table 2 Highest two correlations and associated lags (day) from cross-correlation of mean daily northward wind stress versus maximum daily estuarine salinity for dates given

Year	1 Mar to 30 Sep		15 Jun to 30 Sep	
	<i>r</i>	Lag	<i>r</i>	Lag
2004	-0.54	-1	-0.51	-1
	-0.44	-2	-0.55	-2
2005	-0.21	-1	-0.45	-1
	-0.17	-2	-0.50	-2
2006	-0.27	-2	-0.40	-1
	-0.23	-3	-0.41	-2

centrations (10 to 15 mgm^{-3}) relative to fluvial levels (e.g., Fig. 7, e, k, l, q–u). However, the relative contribution of the oceanic source of chlorophyll to the estuary varied, presumably due to variation in production and delivery of ocean phytoplankton to the coast. An additional pattern of high chlorophyll concentration was found in mesohaline salinities (approximate range 5 to 20 psu) during late summer (Fig. 7, k, r–u). This signal was caused by blooms of the “red water” producing mixotrophic ciliate *Myrionecta rubra*, which commonly form dense and persistent accumu-

lations in the CRE during late summer and autumn (Herfort et al. 2010; Roegner, unpublished data).

Regression statistics in C/S diagrams did not indicate simple conservative mixing characteristics (Table 3). While slopes were generally negative in spring and positive after June, consistent with a switch in delivery of chlorophyll from river to ocean end members, correlation coefficients varied greatly. The large deviations from linearity and the low coefficients occurred in part when large concentrations of *Myrionecta* were present in the mesohaline water during late summer.

Indices of Biophysical Parameters

A time series of the chlorophyll SR depicts a clear seasonal separation of chlorophyll delivery to the estuary (Fig. 8a). From March to June (spring), SR values indicated enhancement of chlorophyll in river water; from July to September (summer), the converse was true. In spring, river water samples had one to nine times the mean chlorophyll concentration of ocean water samples (Fig. 9). In summer, ocean water samples were enhanced one to seven times over river water samples.

Data distribution in relation to cumulative stream flow (SF) showed that most samples were collected at low- or

Fig. 6 Water column salinity (top panels) and chlorophyll (bottom panels) along the South Channel transect measured near the slack high-water period. The examples typify general patterns observed during spring/neap and seasonal conditions.

a Spring tide during the spring phytoplankton bloom. **b** Neap tide during the spring phytoplankton bloom. **c** Spring tide during the summer upwelling season. **d** Neap tide during the summer upwelling season. Salinity isopleths are 2 psu; chlorophyll isopleths are 2 mgm^{-3} . Bottom contours shown in black

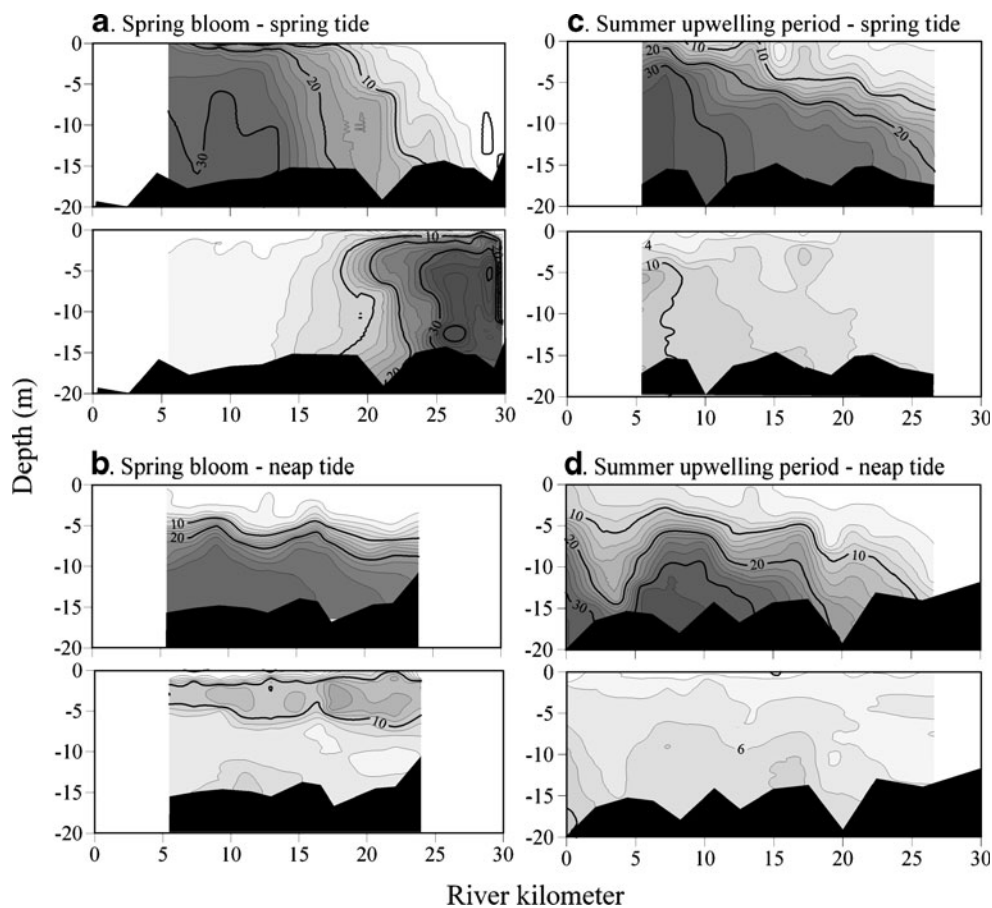
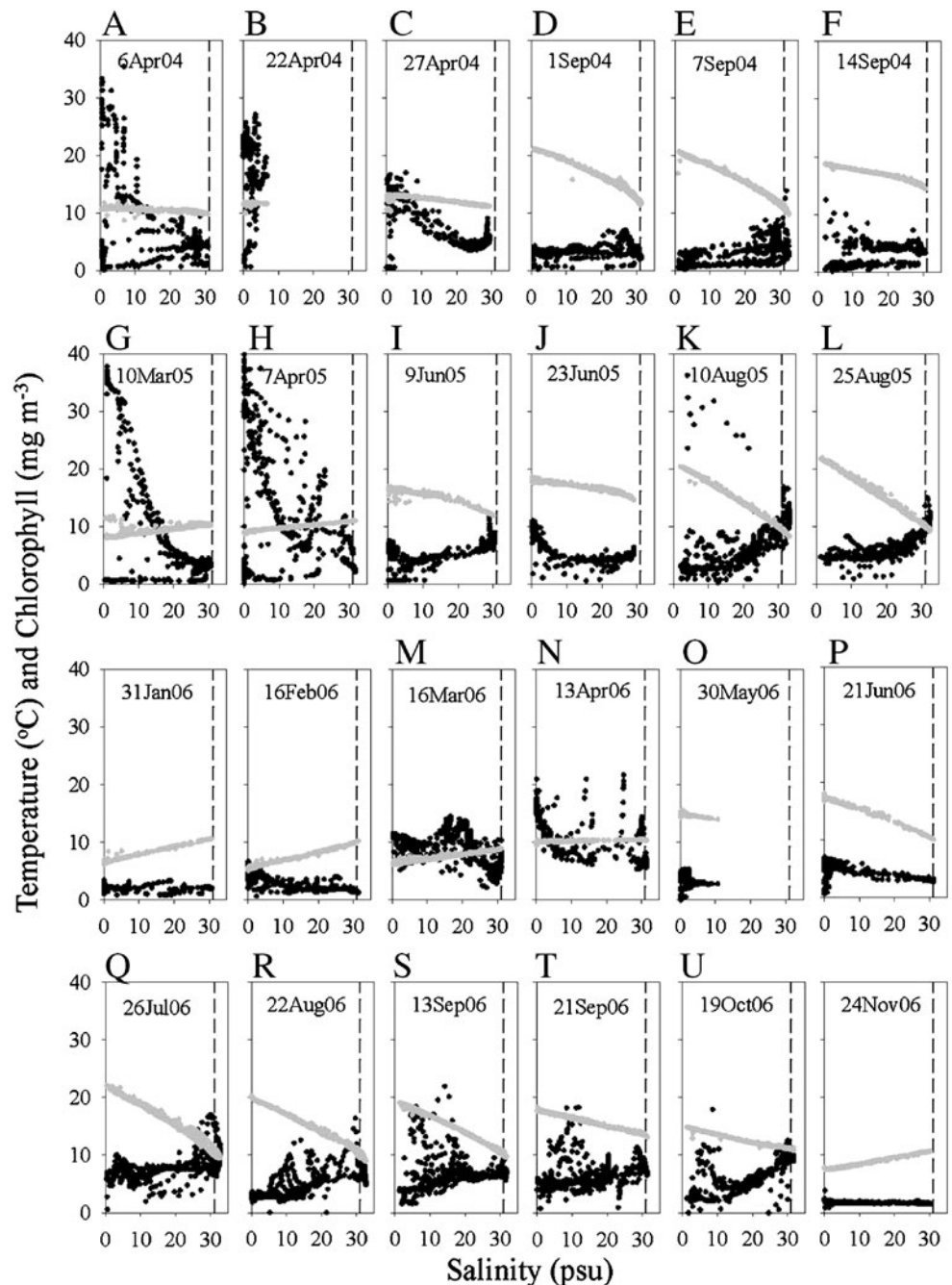


Fig. 7 Temperature–salinity (gray) and chlorophyll–salinity (black) diagrams for South Channel transects for the indicated dates. Dashed vertical line indicates 31-psu threshold for oceanic water. Letters refer to Figs. 3, 4, and 5 and Table 3



medium-flow periods, and only three dates occurred during high-flow periods (Fig. 8b). Ocean advection dominated in summer low-flow periods; riverine sources occurred over a wider range of SF but were highest in low- to medium-flow periods during spring.

Surveys were also made over a range of 4-day cumulative wind stress values (Fig. 8c), with 12 cruises during upwelling conditions and nine during downwelling. Both cruises that failed to encounter salinity of >29 psu were during downwelling periods and medium or high flow. CWS values during upwelling ranged up to -0.5 N m^{-2} , while downwelling wind stresses were clustered

below 0.3 N m^{-2} , with three dates in the “strong” downwelling category. Note that both upwelling and downwelling values occurred in both spring and summer time periods. Upwelling conditions generally resulted in enhancement by the ocean end member (in 67% of cases), while during downwelling the converse trend was observed (57% of cases).

The SN was not sampled evenly: 71% of the 21 cruises were made during spring tide conditions (Fig. 8d). No obvious pattern of SR with SN was observed.

Principal components analysis was used to examine general relationships of the indices outlined above (Table 4).

Table 3 Regression statistics for temperature–salinity (T/S) and chlorophyll–salinity (C/S) relationships measured during hydrographic surveys

Year	Date	T/S			C/S			Cruise
		Slope	Intercept	r^2	Slope	Intercept	r^2	
2004	6-Apr	−0.02	10.8	0.56	−0.43	15.8	0.35	A
	22-Apr	0.04	11.6	0.13	−0.59	19.2	0.03	B ^a
	27-Apr	−0.06	13.0	0.78	−0.22	10.8	0.40	C
	1-Sep	−0.30	21.8	0.98	0.02	2.8	0.05	D
	9-Sep	−0.31	21.2	0.98	0.11	8.0	0.34	E
	14-Sep	−0.13	19.2	0.97	0.07	1.8	0.14	F
2005	10-Mar	0.06	8.5	0.58	−0.70	21.8	0.49	G
	7-Apr	0.06	9.1	0.98	−0.45	18.6	0.19	H
	9-Jun	−0.14	16.7	0.91	0.07	4.5	0.16	I
	23-Jun	−0.10	18.1	0.94	−0.12	7.6	0.43	J
	10-Aug	−0.36	21.2	0.99	0.24	1.3	0.75	K ^b
	25-Aug	−0.37	21.7	0.99	0.19	2.8	0.57	L
	31-Jan	0.14	6.4	0.98	−0.01	2.3	0.11	
	16-Feb	0.15	5.4	0.99	−0.19	4.8	0.66	
	16-Mar	0.08	6.4	0.96	−0.14	10.9	0.27	M
13-Apr	0.02	9.8	0.59	−0.22	14.9	0.47	N	
2006	30-May	−0.03	14.7	0.10	−0.23	4.3	0.18	O ^a
	21-Jun	−0.23	17.4	0.99	−0.07	5.4	0.35	P
	26-Jul	−0.38	22.5	0.98	0.09	6.0	0.24	Q
	22-Aug	−0.33	20.2	0.99	0.12	3.1	0.39	R
	13-Sep	−0.30	19.7	0.99	0.04	6.2	0.02	S ^b
	21-Sep	−0.14	17.9	0.99	0.07	5.6	0.08	T ^b
	19-Oct	−0.12	14.8	0.98	0.23	2.1	0.57	U ^b
	28-Nov	0.10	7.6	0.96	−0.01	1.9	0.24	

Cruise designations are referenced in the figures

r^2 correlation coefficient

^a Cruises where $S_{\max} < 29$ psu

^b Regressions affected by *M. rubra*

Three factors each explained >15% of the variance, but only the first two had at least one significant component (correlation coefficient $\geq |0.60|$). Most variance (42.5%) was contained in factor 1, which exhibited positive associations of wind stress and river chlorophyll and a negative relation for ocean chlorophyll and day of year. Factor 2 variance (19.9% of total) was contained in the spring/neck variable and factor 3 (16.7%) by a mixture of variables with stream flow scoring close to the significance level ($r = -0.58$). Examining the factor loading plot for the first two factors revealed that river chlorophyll and wind stress clustered together (downwelling) while ocean chlorophyll was negatively related to wind stress (upwelling) and clustered closely with the day of year (Fig. 10a). This indicates the increased likelihood of ocean input of chlorophyll as the upwelling season progressed. The plot also suggests a tendency for ocean enhancement to be higher during full moon periods. However, spectral density plots failed to distinguish a spring/neck periodicity in maximum estuarine salinity (data not shown). The factor 1 \times factor 3 plot indicated that both chlorophyll indices were negatively related to stream flow (Fig. 10b).

Discussion

River Sources and Stream Flow

The time series of the source ratio SR indicates a strong seasonal trend in river versus ocean sources of chlorophyll to the Columbia River estuary (Fig. 9). During spring, chlorophyll transport to the estuary was dominated by fluvial processes. High chlorophyll concentration of <4 psu in water indicates a freshwater origin (Fig. 7), and values of the SR were >1 from March through June (Figs. 8a and 9), indicating a river-dominated source. We did not ascertain the phytoplankton assemblage during this study. However, previous work has shown that freshwater diatoms dominate riverine phytoplankton dynamics (Haertel et al. 1969; Lara-Lara et al. 1990; Sullivan et al. 2001). Small et al. (1990) found a seasonal abundance peak during the spring diatom bloom in March and April, followed by decreased levels through autumn (Fig. 7). On the Oregon shelf, light is limiting to phytoplankton growth in winter, and the minimum light intensity threshold of 21 Wm^{-2} does not occur until mid-March (Henson and Thomas 2007). Light

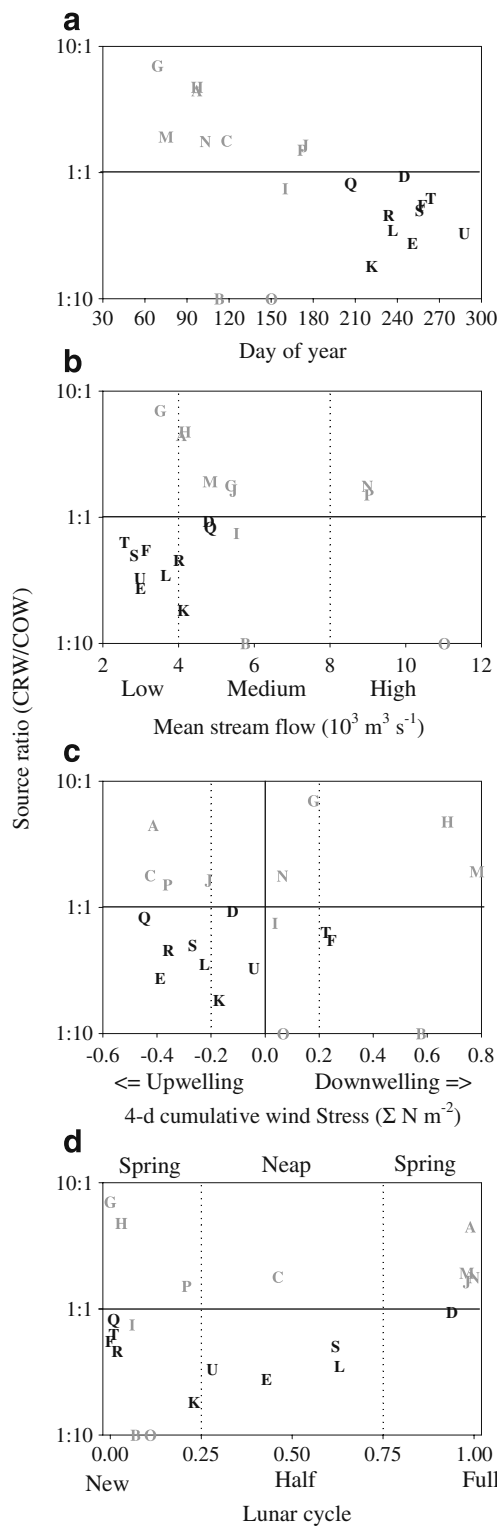


Fig. 8 Source ratio (CRW/COW) in relation to time and physical indices. Ratio is log₁₀-scaled. **a** Day of year. **b** Cumulative 4-day stream flow, SF. *Dashed lines* separate low-, medium-, and high-flow regimes. **c** Cumulative 4-day wind stress, CWS. *Dashed lines* separate low and medium CWS. **d** Spring/neap cycle, SN. *Gray letters*, spring samples (March through June); *black letters*, summer samples (July through September); cruises B and O, all salinities <29 psu

limitation may also be a primary factor limiting algal biomass in the river during winter (Fig. 7; Sullivan et al. 2001).

Stream flow appeared to modulate the magnitude of the spring bloom. The chlorophyll concentration in the high-flow year 2006 was reduced compared to levels in 2004 and 2005 (Figs. 3, 4, 5, and 7). The presumed mechanism is that algal biomass accumulates during transit in low-flow conditions but is minimized when rapidly advected through the system in high flows (Prahl et al. 1998). Maximum spring bloom concentrations exceeded 40 mgm⁻³ in 2004 and 2005, compared to 20 mgm⁻³ in 2006. However, note that chlorophyll concentrations during spring generally remain relatively high even during high-flow years (>15 mgm⁻³; Small et al. 1990; Prahl et al. 1998).

The fate of this fluvial phytoplankton depends on stream flow and tidal factors. Freshwater cells tend to lyse when subjected to salinities of 3–5 psu (Lara-Lara et al. 1990), and the resultant material is converted to detrital particulate and dissolved organic matter. Where this salinity-based transformation takes place is related to flow velocity, stage of tide, and the spring/neap stratification–destratification (Fig. 6). While tidal freshwater stations in the lower Columbia River are exemplified by a well-mixed water column, estuarine stations can be highly stratified. During ebb tides, high-flow periods with minimal salinity intrusion within the estuary, and neap periods of high stratification, freshwater phytoplankton can be transported directly into the coastal ocean in the Columbia River plume (Fig. 6). In contrast, during flood tides, spring tides of increased mixing, and periods of reduced flow, transformations occur within the estuary and often in ETM zones (Baross et al. 1994). ETM form and migrate along the river channel based on salinity and velocity characteristics (Small and Prahl 2004; Jay et al.

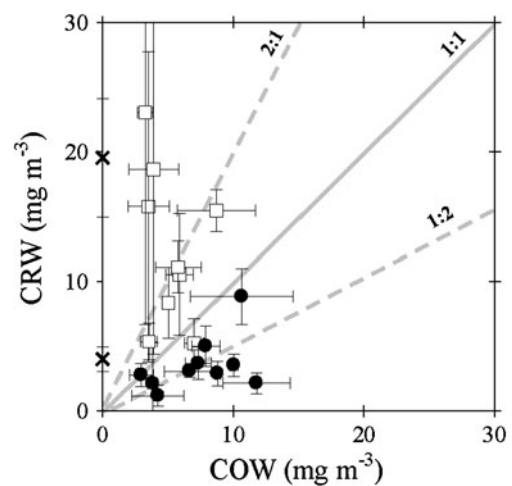


Fig. 9 Scatterplot of mean chlorophyll in river water (CRW) versus mean chlorophyll in ocean water (COW). *Squares*, spring samples (March through June); *circles*, summer samples (July through September); *crosses*, salinity <29 psu. *Error bars* are one standard deviation

Table 4 Principal component eigenvalues for factors 1 to 3

Variable	Code	Factor 1	Factor 2	Factor 3
Day of year	DoY	-0.92	0.15	0.18
4-d cumulative wind stress	CWS	0.61	0.53	-0.12
Stream flow	SF	0.46	-0.55	0.58
Spring/neap	SN	0.07	-0.76	-0.51
Chlorophyll in river water	CRW	0.85	0.13	-0.35
Chlorophyll in ocean water	COW	-0.64	-0.02	-0.48
% Variance		42.51	19.91	16.71
Cumulative% variance		42.51	62.42	79.13

Italicized values are ≥ 0.60

2007). Thus, under some hydrographic conditions, the river can supply fluviially derived organic matter directly to the coast; during other periods, that material is processed within the estuary itself. Tidal and stream flow factors thus modulate the fate of fluvial phytoplankton.

Ocean Sources and Wind Stress

Seasonal cycles of local wind stress influenced the input of high-salinity water and coastal phytoplankton into the Columbia River estuary. The date of the spring transition and the initiation of upwelling varied significantly over the 3-year study period. Before the date of the transition each year, values of SR were >1 , and they remained so (in four of five cases) for 1–2 months afterward (Fig. 11). Based on linear regression of SR by DoT, there was an inferred 68-day lag between the spring transition and ocean import of chlorophyll. By July in each year of our study, all SR values were <1 , indicating an ocean-dominated chlorophyll signal.

The average date of the spring transition, calculated for a 34-yr period as in Shanks and Roegner 2007, is 7 April \pm 24 days (DOY 97). The spring transitions in 2004 and 2006 were within 2 weeks of the mean date (3 April and 22 April), while the transition in 2005 was delayed until around 23 May, over two standard deviations from the mean. As defined by Kosro et al. (2006), the “biological spring transition” lags the physical spring transition by about a month (35 ± 27 days) and usually occurs in mid-May; in 2005, some biological systems did not respond until August (Barth et al. 2007). This lag was also pronounced in our study during 2005 (Fig. 4); downwelling conditions dominated during May and June, while sustained upwelling occurred from late July through August and was associated with relatively high imported chlorophyll levels ($15\text{--}20 \text{ mgm}^{-3}$; Fig. 7, k, l). These results also conform to studies of shelf productivity conducted by Hickey et al. (2006), who found that shelf chlorophyll concentrations remained below 5 mgm^{-3} until July 2005 and increased to around 15 mgm^{-3} in August. While the consequences of this delay in productivity to shelf ecosystems have been discussed (Barth et al. 2007), the effects on the estuarine ecosystem are unknown.

The frequency, duration, and intensity of local wind events also differed substantially between years (Table 1), and this affected patterns of maximum estuarine salinity, which is the tracer for upwelled water. The year 2004 was

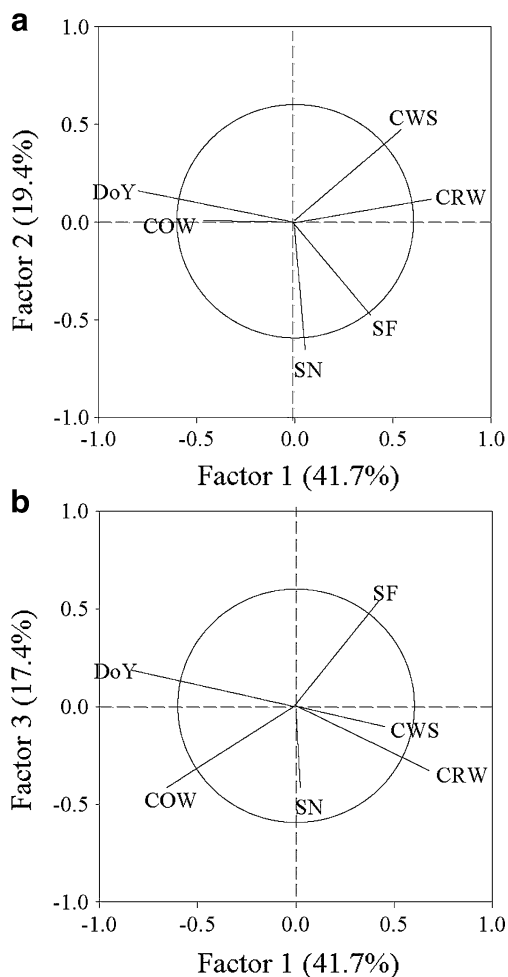


Fig. 10 Principal component, factor loading plots for **a** factor 1 vs factor 2 and **b** factor 1 vs factor 3. Circle denotes 0.6 correlation threshold. Variable codes and eigenvalues given in Table 4

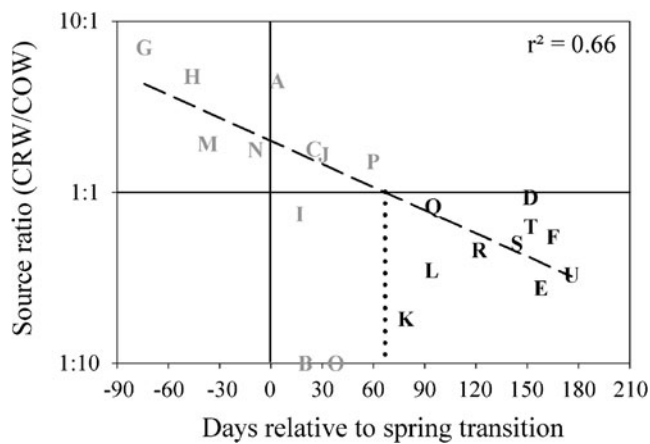


Fig. 11 Source ratio (CRW/COW) in relation to days relative to the spring transition. Ratio is \log_{10} -scaled. *Gray letters*, spring samples (March through June); *black letters*, summer samples (July through September); regression line (*dashed*) does not include cruises B and O, for which all salinities were <29 psu

characterized by a high number of alternating upwelling and downwelling periods, and 2005 was dominated by downwelling conditions or low wind stress until August, while 2006 had relatively sustained upwelling conditions after the spring transition in March, aside from ~ 3 weeks of moderate downwelling-favorable conditions in late May and June. Inspection of the time series of τ_N and S_{\max} reveals that estuarine salinity was highly sensitive to fluctuations and trends in coastal wind stress (Figs. 3, 4, and 5). Time series exhibited rapid fluctuations of S_{\max} with changes from upwelling to downwelling conditions. The largest salinity decreases occurred when strong downwelling events coincided with periods of high stream flow. Using cross-correlation, the best fit of the two time series occurred at lags of -3 to -1 day, indicating a rapid response of S_{\max} to τ_N , with correlations becoming stronger later in the season (Table 2). When upwelling occurred early (2004 and 2006), S_{\max} increased in the estuary earlier than when the spring transition was delayed (2005). These data fit the paradigm of wind stress influencing the type of water masses present near the estuarine mouth, with increasing salinities occurring with strong upwelling wind events and a general trend of increasing salinity in the estuary as the upwelling season progresses.

Wind stress fluctuations also affected chlorophyll concentration in the ocean end member (Figs. 3, 4, and 5). Cruises during periods of active upwelling often exhibited enhanced chlorophyll concentrations in water >29 psu (Fig. 7, e, k, l, q, r, u). During downwelling or before “spin up” of coastal water, lower concentrations and lower salinities were present in the ocean end member (Fig. 7, d, f, i, j, p). Samples in May and June were commonly collected during low wind stress or downwelling conditions during the study years, even when the spring transition had occurred. After the onset

of sustained upwelling, slopes of data points in C/S diagrams were usually positive, indicating higher chlorophyll in higher-salinity water (Table 3). However, transitions from upwelling to downwelling conditions quickly affected estuarine chlorophyll distributions (Figs. 4 and 7, d, e).

Maximum chlorophyll concentrations in high-salinity water were 10 to 15 mgm^{-3} , levels that are similar to those observed on the Washington shelf during upwelling events (Roegner et al. 2002; Hickey et al. 2006) but much lower than concentrations in the river during spring diatom blooms. The fate of coastal phytoplankton in the estuary is uncertain. However, data from benthic diatom surveys indicate that freshwater forms dominate most areas surveyed and that estuarine and marine species were limited to peripheral bays such as Baker Bay (Amspoker and McIntire 1986). It is likely that coastal inputs were proportionally more important to the ecology of the Columbia River estuary before enhancement of fluvial phytoplankton by the hydrosystem (Sullivan et al. 2001).

Regional Comparisons

Most Pacific Northwest coastal estuaries have small watersheds with seasonal rainfall patterns and alternate between terrestrial and oceanic nutrient supply (Colbert and McManus 2003; Sigleo and Frick 2007; Brown and Ozretich 2009). In the winter rainy season, coastal estuaries may provide important sources of nutrients to the ocean during periods of high flushing (Hill and Wheeler 2002). In summer, these estuaries generally exhibit low stream flow, depleted fluvially derived nutrients, and short hydraulic residence times. This results in a decreased importance of riverine and terrestrial sources of organic and inorganic material to estuarine systems. Alternatively, during summer periods, nutrients and phytoplankton generated on the continental shelf during upwelling events can be transported to the coast during subsequent wind relaxation events and then into estuaries through tidal advection (Roegner and Shanks 2001; Roegner et al. 2002; Banas et al. 2007). Oceanic phytoplankton species have been found in estuarine water samples (Haertel et al. 1969; Newton and Horner 2003), and stable isotope analysis indicates that marine-derived nutrients can be incorporated into estuarine benthic food webs (Ruesink et al. 2003; Sigleo et al. 2005). Shellfish toxicity and fishery closures along the Washington coast have also been linked to wind-driven transport of the harmful algal bloom diatom *Pseudo-nitzschia* spp. to the coast (Trainer et al. 2002). Hydrographic and biogeochemical links between upwelling dynamics and coastal estuaries have been found in a number of estuaries in Washington (Pearson and Holt 1960; Roegner et al. 2002; Hickey et al. 2002) and Oregon (Haertel et al. 1969; de Angelis and Gordon 1985; Roegner and Shanks 2001; Colbert and McManus 2003; Hickey et al. 2002;

Brown and Ozretich 2009), as well as further south in California (Martin et al. 2007; Caffrey et al. 2010). It should be noted that these examples of allochthonous coastal production fuelling estuarine dynamics in Pacific Northwest estuaries are contrary to the paradigm of river-borne nutrients driving autochthonous primary and secondary production within Atlantic and Gulf coast estuaries.

The Columbia River estuary differs from other Pacific Northwest coastal systems in its prodigious freshwater export and high fluvial phytoplankton production. Nutrients do not appear to become limiting to riverine phytoplankton (Prahl et al. 1998; Sullivan et al. 2001; Bruland et al. 2008), and river water chlorophyll concentrations can be maintained at relatively high levels ($>6 \text{ mgm}^{-3}$) throughout summer months. Chlorophyll levels can be extremely enriched during the spring bloom. This material likely fuels secondary production in the estuary during transformation in ETM (Baross et al. 1994; Prahl et al. 1997; Small and Prahl 2004) or in the coastal ecosystem after export to the ocean. High primary production in the fluvial zone is thought to be an anthropogenic effect of dam construction, and conditions in the unregulated river were likely characterized by a greatly reduced riverine phytoplankton component and an increase in terrestrial detritus (Sullivan et al. 2001). But despite extensive management of the Columbia River hydrosystem, climatic factors still resulted in large variation in stream flow during our 3-year study.

As in other Pacific Northwest coastal estuaries, the ocean end member contributes ocean-derived chlorophyll and probably nutrients to the Columbia River estuary during summer. Ocean sources dominate estuarine chlorophyll patterns during upwelling periods, but the local wind patterns that control the magnitude and timing of ocean input also exhibit significant interannual variation. One might surmise that strongly pulsed upwelling/relaxation cycles would result in the greatest cumulative transport of ocean phytoplankton to the estuary (as in 2004) because this would favor repeated cycles of ocean production and subsequent advection to the coast. In contrast, sustained upwelling (as in the summers of 2005 and 2006) may lead to the enhanced inwelling of inorganic nutrients and autotrophic production within the system, since phytoplankton in newly upwelled water at the coast may require

time in the photic zone to become densely concentrated (Roegner et al. 2002). As a result of Ekman transport, blooms during active upwelling usually develop tens of kilometers from the shore (Small and Menzies 1981).

An interesting comparison with low-discharge PNW estuaries (i.e., not the Columbia) can be made with the particularly well-studied Galician Rias Baixas of NW Spain (Alvarez et al. 2005). Reports indicate that phytoplankton in these systems can have either autochthonous or allochthonous origins, based partially on species type (diatom versus dinoflagellate) and their relative motility (Fermin et al. 1996; Bravo et al. 2010). In situ growth of diatoms fueled from inwelled nutrients commonly occurs in the Rias when downwelling conditions follow an upwelling episode (Figueiras et al. 2002). The ensuing stratification and reduced flushing tends to stimulate production that fuels a large mussel aquaculture industry (Alvarez-Salgado et al. 1996). However, advection of phytoplankton from the coast also occurs during relaxation or downwelling, typically in late summer, and can include toxic red-tide-forming dinoflagellates (Bravo et al. 2010; Escalera et al. 2010).

Globally, other regions where coastal upwelling occurs, such as along eastern boundary currents, are expected to result in interactions with adjacent estuarine systems analogous to those found in the PNW. Data concerning ocean–estuarine exchange in these regions are sparse; however, a broad comparison of estuaries along the four main upwelling centers reveals that substantial differences exist in the number of systems and the magnitude of their freshwater output (Sherman and Hempel 2009; Sea Around Us 2007; Table 5). The Canary Current Large Marine Ecosystem (LME) is the smallest of the four main upwelling centers (30° N to 10° N ; $1.1 \times 10^6 \text{ km}^2$) and is adjacent to seven estuaries, all which exhibit discharge rates averaging $<10^3 \text{ m}^3 \text{ s}^{-1} \text{ day}^{-1}$. The Benguela Current LME is slightly larger (34.5° S to 13° S ; $1.5 \times 10^6 \text{ km}^2$) and includes six estuaries with discharge rates $<10^3 \text{ m}^3 \text{ s}^{-1} \text{ day}^{-1}$ but also includes the Congo, which has a massive discharge exceeding $45 \times 10^3 \text{ m}^3 \text{ s}^{-1} \text{ day}^{-1}$. The many coastal lagoons in this region may also be impacted by upwelling dynamics. The Humboldt Current LME is the largest upwelling system (40° S to 5° S ; $2.6 \times 10^6 \text{ km}^2$) and has 24 adjacent estuarine systems, 12 with flows $<10 \text{ m}^3 \text{ s}^{-1} \text{ day}^{-1}$ and two that exceed $10^3 \text{ m}^3 \text{ s}^{-1} \text{ day}^{-1}$.

Table 5 A comparison of the number and range of average daily freshwater discharge from estuarine systems bordering the four main upwelling Large Marine Ecosystems

	Upwelling system	River discharge range ($\text{m}^3 \text{ s}^{-1} \text{ d}^{-1}$)					Sum
		$<10^1$	$\geq 10^1$ – 10^2	$>10^2$ – 10^3	$>10^3$ – 10^4	$>10^4$	
	Canary	2	2	3	0	0	7
	Benguela	2	1	3	0	1	7
	Humboldt	12	2	8	2	0	24
Data from Sea Around Us (2007)	California	41	18	8	3	0	70

Few of the estuaries along any of these coasts have been surveyed for linkages with coastal upwelling dynamics. In contrast, the better-studied California Current LME (48° N to 24° N; 2.2×10^6 km²) interfaces with 70 estuaries, 58.6% of which have discharges < 10 m³ s⁻¹ day⁻¹, 37.1% between 10 and 10³ m³ s⁻¹ day⁻¹, and three systems that exceed 10³ m³ s⁻¹ day⁻¹. The Columbia River, with an average daily discharge of 8.2×10^3 m³ s⁻¹ day⁻¹, is the second largest (after the Congo) freshwater source bordering these eastern boundary current LMEs. The Columbia thus stands out as a relatively unique river system bordering an upwelling center.

Conclusions

In the Columbia River estuary, seasonal variation in stream flow and wind stress determined the balance of riverine or ocean end members dominating estuarine chlorophyll patterns. Stream flow influenced delivery of freshwater and riverine phytoplankton to the estuary, while variation in local wind stress controlled upwelling and the delivery of high-salinity water and coastally derived phytoplankton to the estuary. Stratification, mixing, and the spatial distribution of water properties and chlorophyll were influenced by the spring/neap tidal cycle. Due to the water retention afforded by snow pack in the Cascade Mountains, there is a much larger and longer freshwater influence on hydrography and chlorophyll production in the Columbia than smaller systems that drain the low-lying Coast Range. The magnitude of stream flow and the initiation, frequency, duration, and intensity of upwelling-favorable winds are climatically controlled and exhibit large interannual variability. Variations in these forcings have strong ecological ramifications for riverine, estuarine, and ocean ecosystems in the Pacific Northwest and likely along other eastern boundary current coastlines.

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