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Multiple trophic levels fueled by recirculation in the Columbia River plume

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[1] Large rivers represent gateways for the transport of terrigenous and anthropogenic material to the coastal ocean. Here we document a ~700 km^2 recirculation or bulge associated with the Columbia River plume that retains recently discharged river water sufficiently to create a regional bioreactor. Fueled by a fluvial nitrate source, this feature stimulated growth across three trophic levels and may buffer this gateway system during periods of increased warming and stratification that lead to decreased ocean productivity, potentially enhancing production at multiple trophic levels and enriching surface waters far from the river mouth. **Citation:** Kudela, R. M., et al. (2010), Multiple trophic levels fueled by recirculation in the Columbia River plume, *Geophys. Res. Lett.*, *37*, L18607, doi:10.1029/2010GL044342.

1. Introduction

[2] Buoyant river plumes modify the coastal ocean via inputs of terrigenous sediments and nutrients, through enhanced stratification, alterations of the ambient light field, and modifications of coastal circulation [*Hickey et al.*, 2005; *Turner and Rabalais*, 1994; *Ware and Thomson*, 2005]. Coastal ecosystems are both positively and negatively impacted by physical retention mechanisms occurring at multiple scales. These include ~1 day recirculation in the tidal plume formed on every ebb; 3–4 day retention within an anticyclonic re-circulating feature with a continuous input of riverine-borne nutrients; other small, eddy-like recirculations in the far-field plume; and, on the largest scale, enhanced surface-layer response to wind reversals which slow equatorward export of nutrients and biomass from the region. Recent field experiments have documented formation of bulge circulation within two distinct plume systems, the Columbia and the Hudson [*Chant et al.*, 2008; *Horner-Devine*, 2009]. Bulges form due to the combined effect of river momentum, plume buoyancy, and earth's rotation, and trap a fraction of the inflowing river water. The formation of a bulge is unique among the potential plume features because it traps river water with a biogeochemical signature distinct from the surrounding coastal water for a long enough period to generate a significant biological impact. *Chant et al.* [2008] found that bulge formation strongly influences primary productivity, dissolved oxygen levels and the cycling of contaminant metals, with potentially negative environmental impacts associated with the development and persistence of low oxygen zones and from the enhanced lifetimes and enhanced trophic transfer of contaminant metals within the eddy [*Moline et al.*, 2008]. We show that a similar bulge sets up under conditions of high river flow and weak winds in the Columbia River plume. It had significant *positive* biogeochemical impacts on the coastal ocean, partially alleviating the negative consequences of the delayed onset of seasonal upwelling seen during spring 2005 in the California Current System.

[3] The Columbia River is the single largest source of freshwater discharge in the Pacific Northwest [*Naik and Jay*, 2005]. At times, it serves as a moderate source of nutrients to the coastal ocean, but is typically dwarfed by wind-driven coastal upwelling [*Bruland et al.*, 2008]. The delay in upwelling in 2005 resulted in the collapse of the phytoplankton community, causing a cascade effect with negative consequences for higher trophic levels including fish, birds, and marine mammals [*Brodeur et al.*, 2006; *Mackas et al.*, 2006]. During this period, a limited area of the coastal ocean associated with the bulge circulation displayed significantly enhanced biological production, comparable to periods of strong upwelling in 2004–2005. The bulge acted as a biological refuge and bioreactor by simultaneously retaining biological standing stocks for 3–4 days while receiving inputs of elevated macronutrients and trace-metals from the Columbia River outflow, which was the main source of nutrients to the coastal ocean during this time [*Bruland et al.*, 2008].

2. Methods

[4] Intensive surveys of the Columbia River plume were conducted as part of the River Influences on Shelf Ecosystems (RISE) project [*Hickey et al.*, 2010], following shortly after the 2005 spring freshet with peak flow of 10,300 m^3 s^{-1}

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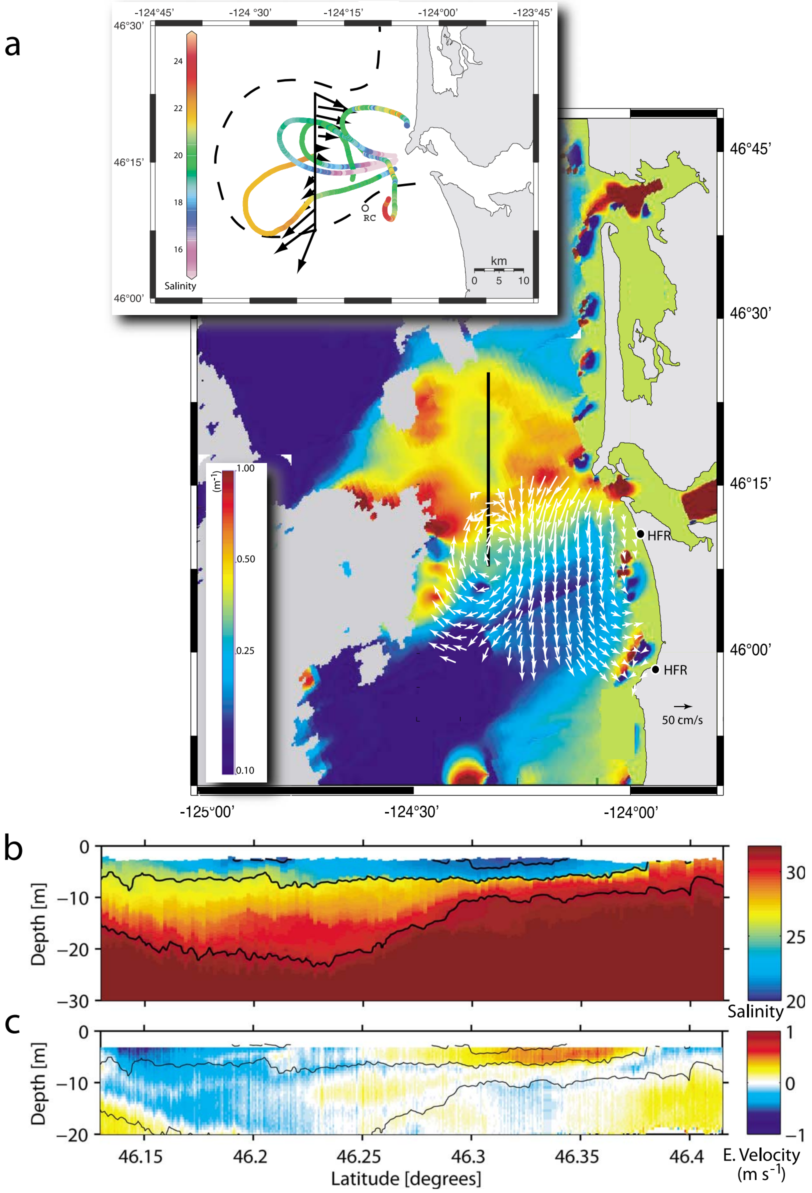


Figure 1. Satellite imagery (a) from the MODIS Aqua sensor (9 June 2005) provides an estimate of colored dissolved organic material absorption, a proxy for surface salinity. Low pass filtered daily-averaged velocity vectors from coastal high frequency radar (HFR) are superimposed. Inset: surface-drogued drifters deployed across the river mouth on 9 June 2005. The open symbol (RC) indicates the position of the mooring; the dashed black line indicates the approximate bulge boundaries and alongshore jet as described by [*Horner-Devine* 2009], and the solid black arrows indicate observed average velocity vectors. Based on drifter trajectories and additional drifter deployments (7–23 June) north, south, and in the vicinity of the bulge, the bulge exhibited retentive properties with substantially decreased (~2–3 fold) alongshore velocities. (b) Salinity cross-section from a towed vehicle CTD along the transect shown by the black line in Figure 1a, 14.7 h after high tide, sampled from south to north. (c) Corresponding east velocity field measured with a side-mounted 1200 Hz ADCP. The solid lines in Figures 1b and 1c denote salinity isohalines of 21, 26, and 32.

on 20 May 2005. RISE included four field efforts during and after seasonally high river flow (May–July 2004–2006) and during a low-flow period (August 2005). Nutrients and trace metals were measured with a standard autoanalyzer and trace metal clean sampling, chlorophyll a with fluorometric determination, and ^{14}C primary production using 24-hour incubations.

[5] Microzooplankton grazing and phytoplankton growth were determined using 24-hour grazer-dilution experiments with deckboard incubations. Samples for phytoplankton enumeration were preserved with acid Lugol's or glutaraldehyde and were analyzed with transmitted and epifluorescence light microscopy. Mesozooplankton data were obtained using a Laser Optical Plankton Counter attached to a Triaxus tow body. The LOPC gathered abundance and size information for particles with an equivalent spherical diameter of 0.09 – 35 mm.

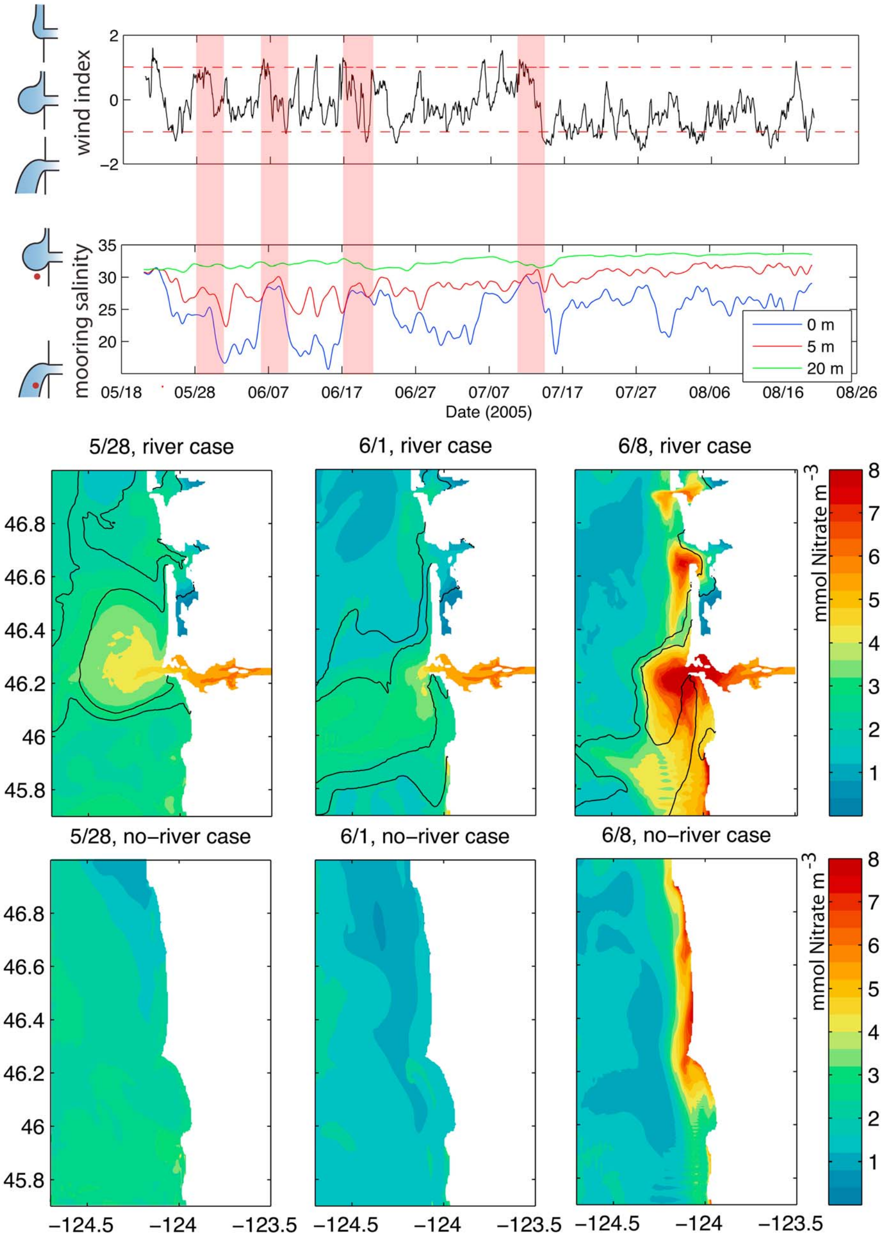
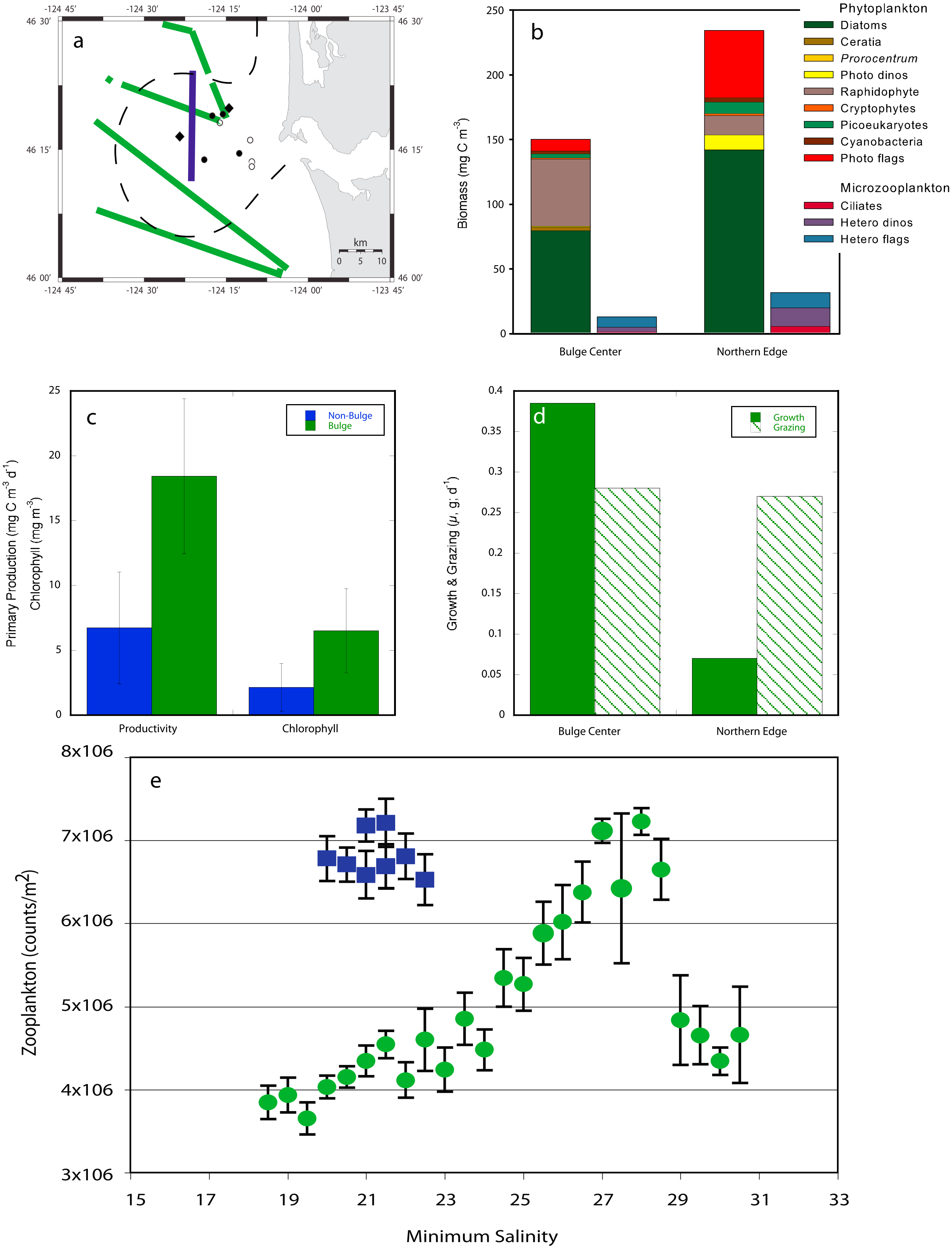


Figure 2. Definition of bulge circulation periods, denoted by red shading, were based on three criteria: 1) (top) a wind stress index [*Whitney and Robert*, 2002]; when absolute values of the index are <1 (~8 m s^{-1}), buoyant flow is not strongly influenced by alongshore wind; 2) (middle) persistent high near-surface (1 m) salinity values at the RISE central mooring, indicative of a northward flowing plume; 3), persistent shoreward flow at 22 m depth estimated from a numerical model [*MacCready et al.*, 2009] for a N–S transect along 124.3° W. The schematics (y-axes, Figure 2, top) depict the plume shape associated with low/moderate/high wind index and low/high salinity values; the RISE mooring is denoted by a red dot. (bottom) A model hindcast of total nitrogen [*Banas et al.*, 2009] tidally averaged and averaged over the top 5 m are shown. Results are shown for the base model case (actual river flow data) and an alternate case in which the Columbia and the smaller estuaries to the north are omitted. Contours of salinity at 24 and 28 are shown in black. On 28 May, nutrients and biomass are markedly higher in the bulge than in surrounding waters, or in the no-river case. On 1 June, as upwelling returns, this accumulation of nutrients and biomass is exported across the shelf and southward. On June 8 a new bulge and new accumulation of nutrients and biomass have begun to form.


a
-124 45′
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km
0 5 10
b
Biomass (mg C m^{-3})
0
50
100
150
200
250
Bulge Center
Northern Edge
Phytoplankton
Diatoms
Ceratia
Prorocentrum
Photo dinos
Raphidophyte
Cryptophytes
Picoeukaryotes
Cyanobacteria
Photo flags
Microzooplankton
Ciliates
Hetero dinos
Hetero flags
c
Primary Production (mg C m^{-3} d^{-1})
Chlorophyll (mg m^{-3})
0
5
10
15
20
25
Non-Bulge
Bulge
Productivity
Chlorophyll
d
Growth & Grazing (μ, g; d^{-1})
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Growth
Grazing
Bulge Center
Northern Edge
e
Zooplankton (counts/m^2)
3x106
4x106
5x106
6x106
7x106
8x106
15
17
19
21
23
25
27
29
31
33
Minimum Salinity

Figure 3

[6] Drifter deployments utilized Brightwaters Corp. model 104A satellite-tracked drifting buoys as described by *McCabe et al.* [2008]. Surface currents were mapped hourly from shore using HF radar.

3. Bulge Circulation

[7] Continuous occupation of a N–S line parallel to the coast (9–10 June 2005) clearly identified a plume of reduced salinity roughly 5–10 m thick with radially symmetric velocities characteristic of anticyclonic rotation (Figure 1). The feature persisted throughout a 19 hr sampling period and was stable through the tidal cycle (Figure 1). The bulge circulation was roughly symmetric, but exhibited enhanced stratification to the north and increased mixing due to turbulent estuary flow to the south [*Horner-Devine*, 2009]. Anticyclonic circulation was evident in drifter trajectories [*McCabe et al.*, 2008], in concurrent high-frequency radar surface current maps (Figure 1), and in numerical simulations of the coastal circulation (Figure 2). Theoretical calculations, model results and observations suggest that the bulge reduced the northward flux of river water in the coastal current by 60–70% for a period of 3–4 days.

[8] Laboratory and modeling studies predict the formation of bulge circulation for rivers of sufficient discharge flow during periods of weak or moderate northward winds [*García Berdeal et al.*, 2002; *Horner-Devine et al.*, 2006] a condition frequently seen during spring and early summer in the Northern California Current. Because *in situ* observations cannot be repeated often enough to assess the frequency of bulge formation, we infer bulge processes from the available field observations and frequency of occurrence from satellite imagery, mooring data, wind measurements, and numerical model simulations. Three other periods in May–August 2005 suggested bulge formation (Figure 2) and met the general criteria of moderate to high river flow, weak winds, and persistent recirculating currents lasting for at least 2 days. Statistical analysis of model results [*Liu et al.*, 2009] similarly identifies a recirculating feature during transitional periods between strong upwelling and downwelling in 2004.

4. The 2005 Warm Anomaly

[9] The period from approximately mid-May to mid-July 2005 was characterized by an absence of sustained upwelling-favorable winds (Figure 2). The Columbia River exhibited higher than normal nitrate concentrations (~13–16 μM versus a historical average of 2.5 μM) and provided >90% of the ambient nitrate in the coastal waters compared to a more typical value of 10% during upwelling [*Bruland et al.*, 2008]. These coastal waters are largely N-limited [*Bruland et al.*, 2008; *Kudela and Peterson*, 2009], and exhibited a 50% reduction in biomass and productivity during spring 2005 resulting from a lack of upwelling-derived macronutrients [*Kudela et al.*, 2006]. While unusual, these conditions are consistent with predicted climate warming scenarios [*Snyder et al.*, 2003], underscoring the importance of the observed coastal response as a harbinger for future changes in coastal ecosystem productivity.

[10] Enhanced productivity is observed in the Columbia River plume regardless of the presence of bulge circulation (ANOVA, $p<0.001$; see Figure S1 of the auxiliary material), but may occur over a large spatial region extending north and south of the bulge [*Hickey et al.*, 2005].[1] While this may ultimately decrease dissolved oxygen along the Washington coast [*Connolly et al.*, 2010], the more immediate effect was positive. Incubation experiments [*Kudela and Peterson*, 2009] show that maximal biomass and phytoplankton productivity are achieved within 3–4 days of enrichment with nutrients. We suggest that the bulge circulation effectively serves as a bioreactor, keeping the plume water from being diluted by non-plume coastal waters for 3–4 days, sufficient for phytoplankton to reach maximum growth rates and for trophic transfer to occur. During June 2005, bulge-influenced ($S<30.5$) productivity values exceeded values for non-bulge plume water from stations in the same geographical region during 2004, June 2005, and 2006, with productivity rates from the bulge region in June 2005 comparable to non-bulge rates measured in August 2005 after the onset of upwelling-favorable winds and renewal of upwelling-derived nutrients. During a transition from weak to strong winds, this productivity must be transported either northward (downwelling) or southward and offshore (upwelling) [*Hickey et al.*, 2005]. When the bulge is not present productivity in the Columbia River plume would be enhanced but diluted during advective transport, limiting trophic transfer.

5. Biogeochemical Response

[11] Biomass within the bulge was dominated by coastal diatoms and an unidentified raphidophyte (Figure 3b);

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2010GL044342.

Figure 3. Biological standing stocks, rate measurements, and community composition from the bulge region. (a) Station positions are shown for bulge (solid) and non-bulge (open) stations sampled between 8–14 June 2005; diamonds indicate grazer-dilution stations. The green (bulge) and blue (non-bulge) lines represent LOPC tracks from 1 June and 9 June respectively. (b) Photosynthetic organisms dominated total biomass, with more heterotrophs at the edge of the bulge compared to within the bulge. The phytoplankton communities were dominated by plankton typically found in coastal waters, as well as an unusual raphidophyte (*Photo* = phototrophic; *Hetero* = heterotrophic; *flags* = flagellates; *dinos* = dinoflagellates). (c) Standing stocks of chlorophyll and carbon-based primary productivity exhibited significant differences for the same spatial region in the presence and absence of the bulge ($n = 4$ for bulge and $n = 4$ for non-bulge; t-test, $p<0.05$; data for bulge period were collected 9–10 June; non-bulge included 7 and 14 June 2005). Error bars represent one standard deviation. (d) Biomass and productivity determined by grazer-dilution techniques at the center and northern edge of the bulge also showed strong differences in phytoplankton growth rates but not microzooplankton grazing rates. (e) Mesozooplankton abundance was determined during a non-bulge period (green) and during the bulge period (blue) using a towed LOPC. Significantly greater number of zooplankton were observed at bulge salinities of ~19–23, suggesting that the zooplankton were attracted to and actively feeding on the enhanced phytoplankton biomass associated with the bulge.

phytoplankton chlorophyll and productivity were enhanced by more than a factor of two relative to non-bulge plume water (Figure 3c). At the northern edge of the bulge, heterotrophic and phototrophic biomass increased as nutrients were drawn down (Figure S2), and there was a shift in the relative biomass of phytoplankton functional groups, with photosynthetic flagellates becoming more dominant as nutrients were depleted. Microzooplankton grazing rates were similar in the presence and absence of the bulge, but growth rates were 4x higher in the bulge center (Figure 3d). Elevated mesozooplankton biomass was also observed (Figure 3e), indicating enhanced trophic transfer. Thus, the bulge provided enhanced nutrients (Figure S2), increased residence time, stronger density stratification, and higher biomass and growth rates, which together enhanced biological production.

[12] Observations presented here document the biogeochemical significance of a river-flow induced anticyclonic bulge circulation. The bulge retains more than 50% of the river discharge on the order of 3–4 days, resulting in enhanced biomass and productivity. Based on enhanced zooplankton standing stock and grazing rates, we infer subsequent transfer of fixed carbon to higher trophic levels. Whereas in the Hudson River plume, bulge circulation and retention act to stimulate hypoxic events and to concentrate contaminants, the Columbia River plume bulge provides a biological refuge during weak or absent upwelling and promotes trophic transfer of carbon to fuel a productive ecosystem. The plume generally serves as a refuge for both juvenile salmonids [*De Robertis et al.*, 2005] and northern anchovy [*Richardson*, 1981]. The peak migration of juvenile salmonids to sea occurs during and after the spring freshet when the bioreactor effect of repeated plume bulges is most likely. We speculate that the multi-day retentive effects of the bulge may result in higher trophic transfer compared to more transient frontal features [*De Robertis et al.*, 2005] and may enhance both salmonid survival and northern anchovy spawning habitat.

6. Conclusions

[13] Multi-year regional-scale patterns in biomass and productivity show the Columbia River Plume to be biologically enhanced relative to the surrounding coastal waters [*Hickey et al.*, 2010], and large-scale spatial trends of increasing northward productivity along the US west coast are evident [*Ware and Thomson*, 2005]. Bulge circulation may buffer the region during periods of suppressed upwelling and productivity, helping to maintain these patterns. Warm periods such as 2005 typically occur every 3–5 years, often coincident with El Niño events; these periods may help to identify ecosystem sensitivity to future climate change [*Schwing et al.*, 2006]. Delayed onset of spring upwelling and earlier peak river inputs to the coastal ocean are consistent with expected changes driven by global warming [*Barnett et al.*, 2005; *Snyder et al.*, 2003], suggesting that the anomalous conditions of 2005 may be a preview of the coastal ocean in a warmer world [*Barth et al.*, 2007]. Changes in global ocean thermal stratification have already modified or reduced plankton production [*Behrenfeld et al.*, 2006]; in the expected warm ocean scenario, the biogeochemical importance of the bulge and other similar coastal retention mechanisms will likely increase in importance, allowing these regions to act as biological oases for multiple trophic levels and enhancing coastal ocean ecosystems adjacent to human population centers.

[14] **Acknowledgments.** We thank the RISE team, especially Parker MacCready, for helpful input, and the National Science Foundation for the financial support for this work. This is contribution 52 from RISE.

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