GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L04607, doi:10.1029/2006GL028069, 2007

Correction published 28 April 2007

# Iron links river runoff and shelf width to phytoplankton biomass along the U.S. West Coast

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Received 4 September 2006; revised 3 January 2007; accepted 9 January 2007; published 27 February 2007.

[1] A poleward increase in phytoplankton biomass along the West Coast of North America has been attributed to increasing river runoff towards the north. We combine streamflow and shelf width data with satellite-derived estimates of phytoplankton biomass to quantify the relationship between these variables. We find that a combination of winter streamflow and shelf width can account for over 80% of the spatial variance in summer chlorophyll within 50 km of the coast. At a given location, interannual variability in streamflow is not associated with interannual variability in chlorophyll. We attribute these relationships to the role of rivers as suppliers of the micronutrient iron, and the role of the shelf as a 'capacitor' for riverine iron, charging during the high-flow winter season and discharging during the upwelling season. Data from the Oregon shelf confirm that, during winter, a significant fraction of riverine iron escapes the estuary and reaches the coastal ocean.
**Citation:** Chase, Z., P. G. Strutton, and B. Hales (2007), Iron links river runoff and shelf width to phytoplankton biomass along the U.S. West Coast, *Geophys. Res. Lett.*, *34*, L04607, doi:10.1029/2006GL028069.

## 1. Introduction

[2] The upwelling system of the West Coast of the U.S. is an important site of air-sea $CO_2$ exchange and deep ocean carbon (C) sequestration [*Hales et al.*, 2005, 2006]. Productivity along this margin also supports an economically significant but fragile fishery. Recent work [*Ware and Thompson*, 2005] has documented a significant correlation between fish yields and phytoplankton standing stock (chlorophyll a).

[3] Despite its importance in terms of C sequestration and fisheries, it is not known what determines the primary productivity in the region or its along-shore and inter-annual variability. *Ware and Thompson* [2005] noted a poleward increase in chlorophyll a (chl), which they speculated to be driven by a poleward increase in river runoff. However, productivity is dominated by the summer upwelling season when river discharge is minimal. We argue here that the gradient in chl is driven by a poleward increase in winter runoff, which supplies the micronutrient iron (Fe) to the shelf. A concomitant increase in shelf width retains riverine Fe where phytoplankton can use it.

## 2. Methods

### 2.1. River Flow and Chlorophyll Data

[4] We divided the U.S. West Coast into 15 sub-regions with latitudinal dimensions of 1° and cross-shelf dimensions of 50 km (Figure 1). Satellite chl data were obtained as 9 km, level 3 standard mapped images from SeaWiFS. Mean monthly chl for 1998–2003 was calculated for each sub-region, which contained, on average, 95 pixels. Potential problems with SeaWiFS chl retrievals in coastal areas include mistaking colored dissolved organic matter (CDOM) and suspended particles for chl. Fluorescence line height (FLH) from the MODIS sensor is free from these interferences. For summer 2005, we found SeaWiFS chl and FLH are strongly correlated throughout the study region ($r = 0.76$, $n = 15$, $p < 0.002$). This indicates that the SeaWiFS chl algorithm is not mistaking suspended sediments or CDOM for chl.

[5] We estimated streamflow to the ocean from the furthest downstream gauging station (FDGS) for every USGS-gauged river. Errors associated with this approach include the effect of un-gauged rivers and losses (gains) through evaporation (precipitation) between the FDGS and the ocean. In our study region this approach agrees well with a global 1° × 1° discharge model that corrects for these uncertainties [*Dai and Trenberth*, 2002]. For all but the Sacramento and Columbia Rivers, the discharge latitude was taken as the latitude of the FDGS. The Sacramento's FDGS is located in the latitude bin to the north of San Francisco Bay. Relocating this gauge was necessary to place the coastal discharge at the correct latitude. The Columbia's FDGS is located close to the northern boundary of the second most northerly bin. Because the Columbia plume is directed northward over the WA shelf during winter, when discharge is highest, we moved its discharge latitude into the most northerly bin.

[6] The average shelf width (distance to the 200 m isobath) was calculated for each latitude bin using the NOAA/NOS medium resolution coastline data and ETOPO2 bathymetry data [*Smith and Sandwell*, 1997]. The adjusted coefficient of determination, denoted $R_a^2$ [*Zar*, 1999], was used to compare multiple linear regression (MLR) models.

### 2.2. Field Sampling

[7] In January and February of 2003 samples for Fe analysis were collected off the OR coast and analyzed as described by *Chase et al.* [2005a]. In January 2005 samples were collected at the mouth of Alsea Bay, OR using a clean pumping system. Iron was determined as per *Chase et al.* [2005a], salinity was measured with a salinometer, total suspended solids (TSS; > 0.45 $\mu$m) were determined gravi-

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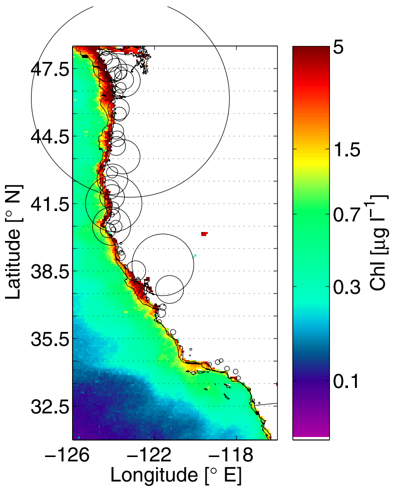

**Figure 1.** Study area. Average chl from SeaWiFS, 1998–2003, is indicated in color (log scale). Circles are proportional to the average annual streamflow at the most downstream USGS gauging station. Also indicated is the 200m bathymetric contour and the 1° latitudinal bins used in the analysis. Puget Sound is not included in the northernmost bin.

metrically and nutrients were determined by continuous flow analysis using standard colorimetric methods.

## 3. Results and Discussion

[8] Our analysis covers the years 1998 (the first complete calendar year of SeaWiFS data) to 2003 (the last complete calendar year of river flow data) and looks at winter (Dec-Jan-Feb-Mar) river flow and the following late summer's (Jul-Aug-Sep-Oct) average chl. This approach minimizes the potential for river-supplied CDOM and suspended particles to confound SeaWiFS chl. Note, however, that *Siegel et al.* [2005] determined that chl errors due to CDOM did not appear to be dominated by riverine inputs. Our analysis (Figure 2a) confirms and quantifies the latitudinal gradient in chl along the U.S. West Coast [*Ware and Thompson*, 2005], with latitude explaining over 70% of the variance in summer chl averaged across all years (Table 1).

[9] Some potential explanations for the correlation between chl and latitude can be rejected immediately. Summer insolation shows no positive trend with latitude over this time period (Figures S1 and S2 of the auxiliary materials).[1] Atmospheric pressure-based, in situ and remote-sensing (QuikSCAT) measurements show upwelling-favorable winds are greater to the south [*Ware and Thompson*, 2005; *Risien and Chelton*, 2006]. All of these wind products have shortcomings. However, QuickSCAT winds, geostrophic winds and model winds are well correlated along the U.S. West Coast [*Pickett and Schwing*, 2006]. QuikSCAT-derived wind stress curl, which also induces upwelling of nutrient-rich waters, has a maximum around Cape Mendocino in summer [*Risien and Chelton*, 2006]. At least at the level of Levitus climatology, nitrate concentrations on upwelled horizons appear invariant with latitude. A poleward decrease in mixed layer depths remains a possibility, but data do not exist at sufficient resolution to address this mechanism.

[10] We propose a mechanism based on Fe availability that depends on delivery of riverine Fe during high-discharge winter conditions, followed by retention of reactive Fe in surface sediments on wide shelves until summer. To examine this, we consider each independent variable separately. Winter river discharge alone explains 50% of the variance in summer chl, while shelf width alone explains 76% (Table 1). A multiple linear regression including both shelf width and river flow further improves the relationship, explaining 82% of the spatial variance in chl. This is a significant improvement over the correlation with latitude alone, and adding latitude as a third independent variable does not increase the explanatory power significantly (Table 1). This suggests that most of the latitudinal dependence of chl is a result of the co-varying river discharge and shelf width. These patterns hold when we consider chl within 100 km from shore, when we consider the median or geometric mean in space and/or time of chl and/or river flow, and when we consider annual chl and annual river flow.

[11] In some Fe-limited regions, satellite-derived estimates of biomass from chl overestimate phytoplankton carbon [*Behrenfeld et al.*, 2006]. This means the true latitudinal gradient in biomass may be greater than estimated here, as we postulate that Fe limitation (and therefore any possible overestimate of chl) increases equatorward.

[12] The case for Fe-limitation in U.S. West Coast waters is complicated. Upwelling-source waters do not contain sufficient Fe to support full consumption of the ample available nitrate [*Bruland et al.*, 2001]. Atmospheric inputs of Fe have been assumed to be minor since offshore wind events are rare. Direct riverine inputs have also been considered minor, because although river water typically

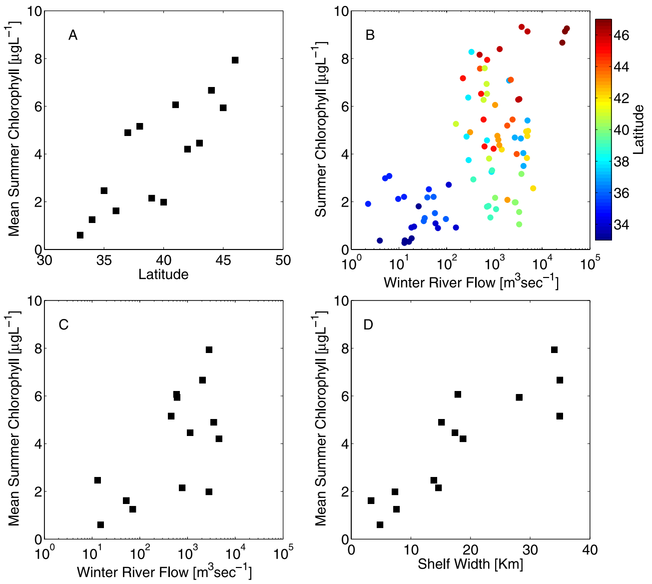

**Figure 2.** Scatter plots of chl and environmental predictor variables. (a) Summer chl as a function of latitude. (b) Summer chl as a function of winter river flow, with each point corresponding to a single year and color-coded by latitude. (c) As in Figure 2b, except values in each latitude band have been averaged across all years. (d) Summer chl and shelf width.

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2006GL028069.

**Table 1.** Multiple Linear Regression Analysis for Variables That May Predict the Distribution of Summer Chl Within 50 km From Shore Along the West Coast of the United States, 1998–2003[a]

| Predictor Variables for Summer Chlorophyll | $R_a^2$ |
|---|---|
| Latitude | 0.71 |
| Winter River Flow (log) | 0.50 |
| Shelf Width | 0.76 |
| Shelf Width and Winter River Flow (log) | 0.82 |
| Width and Latitude and Winter River Flow (log) | 0.83 |

[a] All $R_a^2$ values are significant at the p = 0.05 level.

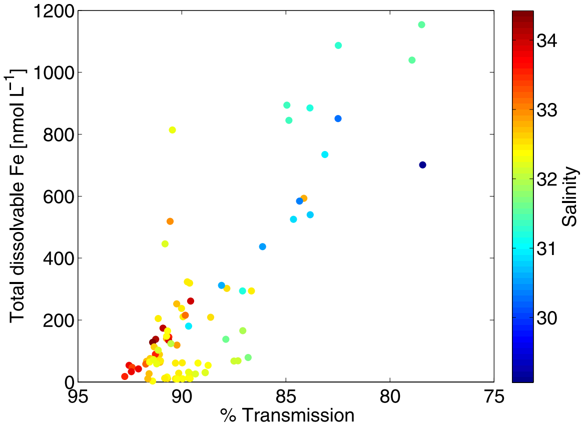

**Figure 3.** Relationship between total dissolvable Fe concentration and light transmission for samples collected in winter 2003 on the OR shelf. Samples are color-coded by salinity.

contains orders of magnitude higher dissolved Fe concentrations than does ocean water, classical studies have shown that nearly all riverine dissolved Fe is lost upon mixing in estuaries [*Boyle et al.*, 1977]. Furthermore, surface dissolvable Fe concentrations off Monterey Bay were roughly six-fold lower in a high river-flow, El Niño year, than in a normal low-flow year [*Johnson et al.*, 1999].

[13] Our analysis supports the idea that rivers do not *directly* supply dissolved Fe to surface waters during the summer. If this were the case, one would expect to find a correlation between years of strong streamflow and years of greater chl. This is not found; for a given latitude bin, inter-annual variability in chl is not correlated with variability in streamflow (Figure 2b). This result also holds if we consider summer instead of winter streamflow and if we look at chl in the bin to the south of the river flow, to account for mean equatorward flow during summer.

[14] Data from the OR coast suggest that rivers are the *ultimate* source of Fe to the shelf and to upwelled water. Specifically, we propose that West Coast rivers deliver significant amounts of Fe to the shelf during high-flow winter conditions, this Fe accumulates on the shelf, and is remobilized for phytoplankton use during summer. In order for this to be the case, riverine Fe must first escape the estuaries and reach the coastal ocean, in contrast to the conclusions of earlier studies on east coast estuaries [e.g., *Boyle et al.*, 1977]. Several lines of evidence support this. We observed high concentrations of total dissolvable Fe (unfiltered samples acidified to pH < 2 for months) on the OR shelf during winter (Figure 3). These concentrations are about an order of magnitude higher than concentrations observed during the summer [*Chase et al.*, 2005a]. Furthermore, the highest Fe concentrations are associated with the lowest salinity waters. Significant inputs of dissolvable Fe (<10 $\mu$m, pH 3 [*Chase et al.*, 2005a]) are also associated with low salinity waters affected by winter coastal river runoff on the OR coast [*Wetz et al.*, 2006]. These observations are consistent with the near-conservative behavior of total Fe observed in some east coast estuaries [*Mayer*, 1982].

[15] These high concentrations of river-derived Fe in coastal waters suggest that during the winter, when river flow is high and shelf and estuarine productivity is low, the small estuaries along the OR coast are exporting a significant fraction of the incoming total riverine Fe. Observations at the restricted mouth of the Alsea Estuary (~44.5°N) in January 2005 confirm this (Figure 4). Concentrations of dissolved Fe (dFe; <0.45 $\mu$m), macronutrients and TSS were all vertically homogeneous and elevated on the ebb tide relative to the flood tide and high-tide slack. Iron shows an enrichment at ebb tide of ~40% over flood tide.

[16] High-tide samples all appear typical of non-plume wintertime coastal waters with respect to salinity, nutrients and Fe [*Wetz et al.*, 2006]. The salinity profiles suggest that the ebb-tide water consists of about 5% fresh river water, while the dissolved Fe enrichment (about 15 nM) over ocean conditions amounts to about 2.5% (given USGS measurements) to 15% (given our measurements; not shown) of the primary river dissolved Fe concentration. Thus ebb tide water discharging from the estuary mouth to the coastal ocean carries at least 50%, and as much as 100%, of the dissolved Fe that would be predicted based simply on conservative mixing.

[17] River flow during this time period was about 60 $m^3 s^{-1}$, less than two-thirds of the average January discharge for the prior decade. The high dissolved Fe efflux from this estuary—several-fold greater than predicted by *Boyle et al.* [1977]—does not appear to require extreme flood events as studied by *Wetz et al.* [2006]. Our measurements from the OR coast therefore indicate that during winter a large fraction of riverine dissolved Fe reaches the coastal ocean.

[18] In order for winter riverine Fe to support high productivity during summer upwelling conditions, it must be retained on the shelf in intervening months. Wintertime

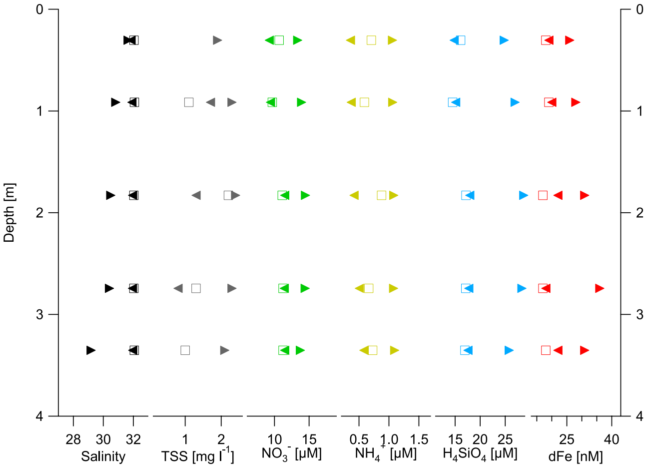

**Figure 4.** Chemical properties at the mouth of Alsea Bay, OR, 12 January 2005. Samples were collected at ebb tide (right-facing triangles), flood tide (left-facing triangles), and high tide (squares).

circulation patterns facilitate this, with a strong downwelling front isolating shelf waters from exchange with the open ocean [*Wetz et al.*, 2006]. Winter total dissolvable Fe concentrations are positively correlated with particle concentration, suggesting that this Fe is primarily associated with particles (Figure 3). If this reactive Fe phase is stored in seafloor sediments where it is remobilized by suboxic diagenetic processes [*Berelson et al.*, 2003], it can be released to the water upwelled through the bottom boundary layer during summer [*Perlin et al.*, 2005]. The shelves thus act as a capacitor for Fe, charging with river-source Fe in winter and discharging it during upwelling conditions.

[19] Several studies have suggested a link between a narrow continental shelf and susceptibility to Fe limitation [*Johnson et al.*, 1999; *Bruland et al.*, 2001; *Chase et al.*, 2005b]. The wider the shelf, the greater the likelihood of retention of riverine Fe, and the greater the opportunity for upwelled waters to interact with shelf sediments and become enriched in Fe. The good correlation we find between shelf width and chl is consistent with this interpretation.

[20] In summary, the data presented here show that the poleward increase in chl along the U.S. West Coast is correlated with a poleward increase in shelf width and streamflow, both of which contribute to greater Fe availability to the north. Winter river runoff supplies Fe to the shelf, in both dissolved and particulate form. Downwelling conditions during winter isolate the coastal ocean from the open ocean and help retain this Fe on the shelf. A large fraction of the Fe exported from rivers is thus ultimately delivered to the sediment as flocculants or via scavenging rather than lost to the open ocean. This winter-derived Fe is then remobilized during the summer upwelling season, where it fuels phytoplankton productivity. The shelf acts as a large capacitor, charging in winter with riverine Fe and dampening year-to-year fluctuations in riverine Fe flow. In regions of the coast with a relatively broad shelf and large riverine inputs (OR and WA coasts), phytoplankton productivity is not limited by Fe [*Chase et al.*, 2005a; *Lohan and Bruland*, 2006] and nearly all available $NO_3$ and considerable amounts of $CO_2$ are consumed within about 20 km of the coast [*Hales et al.*, 2005, 2006]. Regions with narrower shelves and reduced river discharge can experience incomplete macronutrient uptake and Fe-limited productivity [*Hutchins and Bruland*, 1998; *Bruland et al.*, 2001].

[21] Several approaches can be taken to test our hypothesis. First, the availability of high-resolution, in situ observations of chl, productivity, wind stress and curl, mixed layer depth and nutrient concentrations would remove any doubts about the validity of remotely-sensed measurements. Second, verification through in situ observations of a poleward increase in Fe stress during summer would confirm the proposed mechanistic link between shelf width, river flow and phytoplankton biomass. Finally, additional insight could be gained by examining large-scale relationships between shelf width, chl and river runoff in other eastern boundary current regions such as South America and Africa.

[22] **Acknowledgments.** Roseanne Schwartz and Linda Baker were critical for success at sea, and Roseanne Schwartz, Dale Hubbard and Joe Jennings assisted with analytical work. We thank Rob Wheatcroft, Jim McManus, Dudley Chelton and Craig Risien for helpful discussions. Comments from two anonymous reviewers significantly improved the manuscript. This work was supported by the National Science Foundation (grants OCE9907953 to A. van Geen and OCE9907854 to Burke Hales). SeaWiFS chlorophyll data were provided by the SeaWiFS Project, NASA/Goddard Space Flight Center and ORBIMAGE: ftp://oceans.gsfc.nasa.gov/. Stream flow data were obtained from the USGS (http://nwis.waterdata.usgs.gov/usa/nwis/monthly).

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