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Coastal iron and nitrate distributions during the spring and summer upwelling season in the central California Current upwelling regime

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ABSTRACT

Distributions of iron and nitrate in the central California Current System upwelling regime (cCCS) from 34 to 41°N were determined during cruises in May 2010 and August 2011. High spatial and temporal resolution data for dissolved Fe and NO_3^- (nitrate+nitrite) in the cCCS from this study greatly expands upon previous studies that were narrower in scope (e.g., focused on just the Monterey Bay region). Shelf sediments from mid-shelf mud belts in this region provide the dominant source of Fe, and there are areas in the cCCS where insufficient Fe is upwelled to accompany elevated levels of other macronutrients (nitrate, phosphate, silicate) to fuel extensive diatom blooms. Surface dissolved Fe concentrations were related to continental shelf width and upwelling strength, and surface Fe concentrations tended to be lower in the late summer than early spring. We present extensive benthic boundary layer (BBL) dissolved and leachable particulate Fe data from both seasons in the mid-shelf region along the central California coast. Leachable particulate Fe concentrations were strongly related to the width of the mid-shelf mud belts (i.e., the continental shelf between the 50 and 90 m isobaths). Dissolved Fe concentrations in the BBL over the mid-shelf were generally highest in wide mud belt areas as well as in areas with very low dissolved oxygen concentrations but did not show a clear seasonal trend. Evidence for probable Fe limitation in upwelled waters was found by using surface dissolved Fe:NO_3^- ratios and the estimated specific growth rate of coastal diatoms based on either Fe or NO_3^- concentrations. Several coastal upwelling regions with only moderate to narrow continental shelves (Pt. Arena to Cape Mendocino and the Big Sur Coast) exhibited evidence for Fe limitation in both the spring and summer upwelling seasons.

1. Introduction

Eastern boundary upwelling systems account for a disproportionally high percentage of global primary productivity relative to their spatial area (Carr, 2002) and are therefore important settings in which to investigate controls on phytoplankton productivity. Upwelling in the California Current System (CCS), the eastern boundary regime of the North Pacific subtropical gyre, exhibits strong seasonality between the fall/winter and spring/summer seasons. The spring transition has been well documented (Huyer, 1983; Lynn and Simpson, 1987; Strub et al., 1987) where a shift in atmospheric wind patterns leads to primarily equatorward, alongshore winds off the coast of North America interspersed with short, wind reversals and relaxation periods. Ekman transport associated with the alongshore winds moves surface waters in the coastal CCS offshore leading to the upwelling of subsurface water along the coast. Cold, salty, nutrient rich water upwells onto the continental shelf at velocities between 10 and 20 m $days^{-1}$ (Checkley and Barth, 2009). Upwelling favorable conditions persist throughout the spring and summer, fueling biological growth along the coast.

Carr and Kearns (2003), in a detailed comparison of eastern boundary current systems, reported that biomass sustained by a given macronutrient concentration in Atlantic eastern boundary current systems was twice as large as those systems in the Pacific. The authors concluded “It is not clear whether the apparent difference in biomass supported by available nutrients is due to differences in the efficiency of the phytoplankton community, perhaps related to the availability of iron, or to grazing pressure.” The cCCS, an area with low dust inputs and a relatively narrow shelf, was one of the locations with lower than expected biomass per nutrient concentration.

Though the CCS is one of the most productive marine ecosystems, there is evidence that certain regions within this coastal upwelling regime experience Fe-limitation of diatom blooms (Firme et al., 2003; Hutchins et al., 1998; King and Barbeau, 2007). Coastal diatoms can multiply rapidly when supplied with adequate nutrients, and as large phytoplankton, can become decoupled from their grazers thus allowing extensive blooms to

Abbreviations: cCCS, central California Current System; Fe, iron; NO_3^-, nitrate; BBL, benthic boundary layer; chl *a*, chlorophyll *a*.

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occur. Under these bloom conditions, diatoms can quickly deplete the ambient macro and micronutrient supplies. In contrast, picoplankton populations are heavily controlled by their quickly growing grazers, and thus are not allowed to bloom and deplete the nutrient supply.

There is relatively low atmospheric input of Fe off the coast of California (Fung et al., 2000; Mahowald et al., 2005). Without external inputs of Fe, coastal upwelling of subsurface water with approximately 15–30 μmol L^{-1} NO_3^- will generally have <1 nmol kg^{-1} Fe to accompany the flux of NO_3^-, a concentration too low to allow for the full drawdown of NO_3^- by coastal diatoms (Bruland et al., 2001). Winter storms in California deliver a high sediment load to the ocean via rivers, much of which is deposited on the continental shelf mud belts at depths of 50–90 m (Wheatcroft et al., 1997; Xu et al., 2002). A wider continental shelf between these isobaths provides a larger surface area upon which this sediment load can be deposited and a larger surface area for the overlying water column to be in contact with mid-shelf sediments. During coastal upwelling, if waters are not too strongly stratified, upwelling source water is from the benthic boundary layer (BBL), which will lead to enrichment in certain trace metals, especially Fe and Mn (Johnson et al., 1999). Therefore, a key external source of Fe in the California upwelling regime is associated with the BBL overlying these mud belt sediments on the continental shelf between 50 and 90 m deep; upwelling of water from the BBL can deliver re-suspended, Fe-rich particles to the surface (Johnson et al., 1999). In addition, as a result of organic matter oxidation and resultant oxygen depletion in the continental shelf sediments, there is a large dissolved Fe(II) flux out of the sediments, which is a significant source of Fe from the continental shelf that can be upwelled to the surface ocean (Berelson et al., 2003; Elrod et al., 2004).

Previous studies have shown that a “mosaic” of Fe-limitation exists off the coast of California with Fe-replete conditions in areas of a wide continental shelf (Año Nuevo) and Fe-limiting conditions in areas of a narrow continental shelf (Big Sur, Point Arena) (Bruland et al., 2001; Hutchins et al., 1998; Firme et al., 2003). Chlorophyll concentrations off the coast of California have a close correlation to Fe concentrations, indicating the key role that Fe plays in the ecosystem (Chase et al., 2007; Elrod et al., 2008). Chase et al. (2007) found chlorophyll concentrations along the West Coast of the US to be correlated with both winter river flow and the width of the shelf—both factors that would increase the external Fe supply to the system.

Here we present an overview of the coastal sources and distributions of Fe and NO_3^- in the cCCS between 34 and 41°N (Pt. Conception to north of Cape Mendocino) during two cruises in May 2010 and August 2011. We present data from the BBL over the mid-shelf and associated surface water transects in both the coastal and offshore regions. Characterization of these coastal sources of Fe is not only important in understanding delivery of Fe to the surface in the coastal upwelling regime, but also in determining the potential source of Fe to the offshore transition regions of the CCS.

2. Methods

2.1. Study site and sample collection

Samples for this study were collected on two cruises aboard the R/V Pt. Sur in the cCCS from May 7 to 25, 2010 and from August 16 to September 1, 2011. Surface hydrographic data (temperature, salinity, and fluorescence) were obtained using the ship's flow-through seawater underway data acquisition system (UDAS). Surface water sampling was conducted along several transects between Cape Mendocino and Point Conception. Fig. 1 shows the coastal (red) and offshore (black) surface transect locations with satellite sea surface temperature (SST, NOAA POES AVHRR satellite via the CoastWatch program) for the May 2010 and August 2011 cruises. Surface transect samples were collected using a trace-metal clean “GeoFish” sampling system (Bruland et al., 2005). Vertical profiles and BBL samples for trace metals were obtained using 8L Teflon™ coated GO-Flo™ bottles (General Oceanics) deployed on a Kevlar™ hydroline (Bruland et al., 1979). Water column hydrographic, dissolved oxygen, beam attenuation, and nutrient data were collected using the R/V Pt. Sur's rosette system with a Seabird conductivity, temperature, depth (CTD) sensor, fluorometer, dissolved oxygen sensor, transmissometer, and Niskin™ bottles. At BBL stations, CTD sensor data (temperature, salinity, beam attenuation, and dissolved O_2) were used to

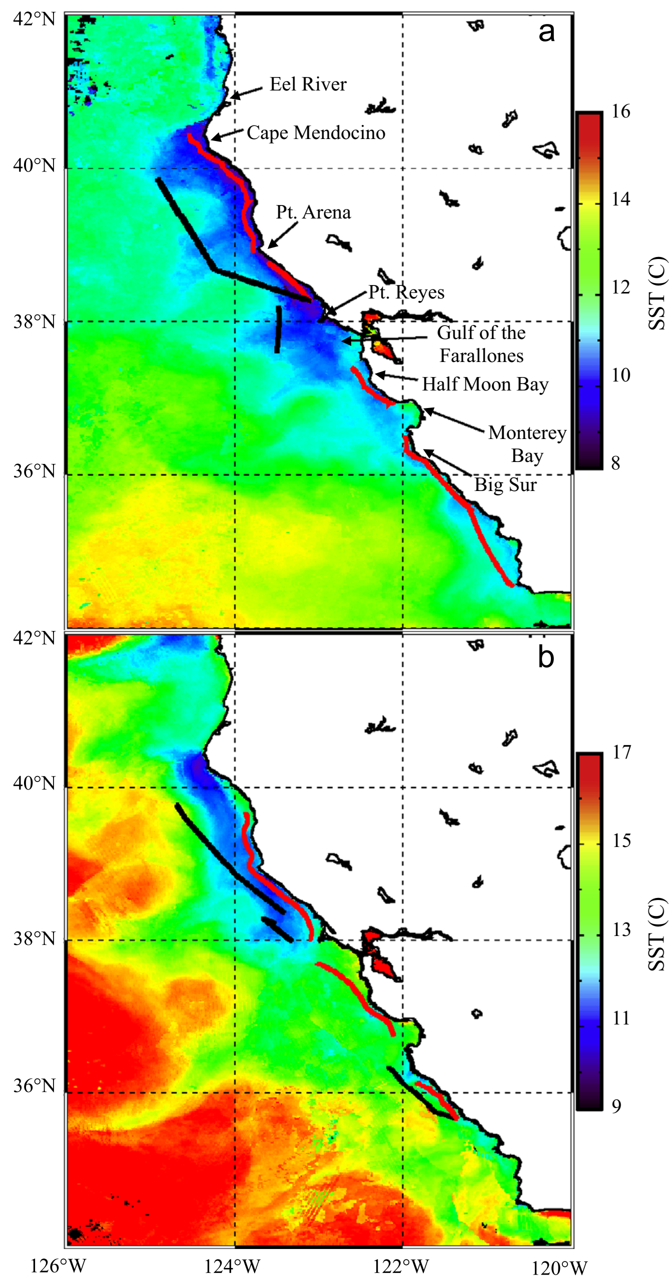

Fig. 1. Surface transect locations for (a) May 2010 and (b) August 2011 with satellite sea surface temperature (SST) for clear days during the two cruises. Note the different SST scales for (a) and (b). For the remainder of this study, the red transects are “coastal” and the black transects are “offshore”.