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The central California Current transition zone: A broad region exhibiting evidence for iron limitation

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ABSTRACT

The transition zone (TZ) of the central California Current upwelling system (cCCS) is the boundary between the cold, saline, coastally upwelled water and the warm, less saline, oligotrophic waters of the offshore California Current (CC). The TZ is a broad region that regularly exhibits chlorophyll concentrations of 1–2 $\mu g\,L^{-1}$ throughout the spring, summer, and fall seasons. Surface transect and vertical profile data from three cruises (May 2010, June 1999, and August 2011) between 34 and 42°N show residual nitrate concentrations (5–15 μM) and low Fe concentrations (most < 0.2 nmol kg^{-1}) in the TZ. We therefore suggest that much of the TZ of the cCCS is an Fe-limited, high nutrient, lower than expected chlorophyll (HNLC) region. The main source of Fe to the cCCS is from upwelling through the benthic boundary layer (BBL) over the continental shelf sediments. Iron and NO_3^- in coastally upwelled water are transported via offshore moving filaments into the TZ. However, since some coastal upwelling regions with narrow continental shelves do not have much Fe to begin with, and since Fe is drawn down more rapidly relative to NO_3^- due to biological assimilation and scavenging, these filaments transport low concentrations of Fe relative to NO_3^- into the TZ. Weak wind curl-induced upwelling and vertical mixing in the TZ also deliver Fe and NO_3^- to the surface but at lower concentrations (and lower Fe:NO_3^-) than from strong coastal upwelling. Mesoscale cyclonic eddies in the TZ are important to consider with respect to offshore surface nutrient delivery because there is a marked shoaling of isopycnals and the nutricline within these eddies allowing higher nutrient concentrations to be closer to the surface. Since wind curl-induced upwelling and/or vertical mixing occurs seaward of the continental shelf, there is not enough Fe delivered to the surface to accompany the NO_3^-. By using Fe:NO_3^- ratios and calculated specific growth rates for diatoms, we demonstrate that the TZ of the cCCS shows evidence for Fe limitation of diatom blooms. The TZ also appears to progress further into Fe limitation as the upwelling season progresses from spring into late summer. This study provides some of the first field data to suggest that Fe is a critical bottom up control on the ecosystem in the TZ of the cCCS.

1. Introduction

The California Current System (CCS), an eddy-rich eastern boundary current, is a highly productive marine ecosystem. In the spring, a large-scale atmospheric shift in wind patterns leads to predominantly equatorward, along-shore winds with short, interspersed reversals. Ekman transport along the coast associated with alongshore winds moves surface waters in the CCS offshore leading to upwelling of subsurface water near the coast at rates upwards of 10–20 m day^{-1} (Checkley and Barth, 2009; Strub et al., 1987). This cold, high salinity, nutrient rich water generally leads to enhanced phytoplankton growth, though there are some coastal upwelling regions in the central CCS (cCCS) that demonstrate evidence for Fe limitation of phytoplankton growth (Hutchins et al., 1998; Bruland et al., 2001; Firme et al., 2003; Biller et al., 2013).

The boundary between coastally upwelled water and warm, low-salinity, nutrient-depleted offshore water in the CCS is known as the transition zone (TZ). The TZ covers the region between the narrow band of coastal upwelling (within 50 km of the coast) and the offshore oligotrophic waters of the CC (>300 km offshore) (Lynn and Simpson, 1987; Kosro et al., 1991). The width of the TZ can be up to a few hundred kilometers and varies seasonally with its widest time in summer and fall (Lynn and Simpson, 1987; Kosro et al., 1991). The TZ is dominated by mesoscale eddies and meanders of the coastal upwelling jet which foster the interaction of coastally upwelled water with offshore water. Often mesoscale eddies in the TZ occur in counter-rotating dipole pairs (Mied et al.,

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

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1991) with an anti-cyclonic eddy to the north of a cyclonic eddy leading to hammerhead shaped SST patterns. These sets of dipole eddy pairs occur seasonally in the TZ, and it is the filaments between these eddies that promote the offshore transport of coastally upwelled, nutrient rich water. Additionally, the filaments are preferentially found in regions of coastal topographic features (Kosro et al., 1991; Oke et al., 2002; Barth et al., 2005) such as Pt. Arena (39°N) (Halle and Largier, 2011).

In addition to coastal upwelling, there is also wind stress curl-driven upwelling where horizontal differences in wind stress cause differences in Ekman transport. Wind stress amplitude is generally greater offshore than near the coast, causing an area of surface divergence as offshore water undergoes more horizontal displacement than coastal water. Upwelling on the order of 0.1–0.2 m d^{-1} occurs through this curl-driven upwelling – an order of magnitude less than coastal upwelling. However, since the geographic area over which this curl-driven upwelling occurs is suggested to be much larger (18–22x larger) than the region of coastal upwelling, it is estimated that a greater volume of water is upwelled via wind stress curl than by coastal upwelling (Rykaczewski and Checkley, 2008). Differences between these two types of upwelling have large consequences for nutrient input to the photic zone and for phytoplankton growth. Coastal upwelling can deliver high concentrations of macro and micronutrients to the surface and allow larger phytoplankton to grow. Much weaker curl-driven upwelling offshore delivers lower concentrations of nutrients leading to the growth of smaller phytoplankton (Rykaczewski and Checkley, 2008).

In addition to the transport of coastally upwelled water offshore, another source of nutrients to the surface waters of the TZ can be from the upwelling and shoaling of isopycnals within strong cyclonic eddies. Shoaling of the nutricline together with wind-induced vertical mixing and/or wind curl-driven upwelling can enhance nutrient input within cyclonic eddies relative to what would occur in an area without eddies or within an anti-cyclonic eddy. A similar mechanism of nutrient delivery associated with the shoaling of isopycnals in cyclonic eddies was proposed by McGillicuddy et al. (1998) in their study of mesoscale activity in the Sargasso Sea.

Fig. 1 presents a monthly average of satellite derived surface chlorophyll-*a* (chl-*a*) concentrations in the cCCS from August 2010. Highly elevated chl-*a* concentrations (~25 μg L^{-1}) occur along the coast (red) in nutrient rich regions over a broad continental shelf such as the Gulf of the Farallones and Monterey Bay, and extremely low chlorophyll concentrations (0.01–0.1 μg L^{-1}) occur in the offshore, nutrient-depleted CC (blue). Intermediate chl-*a* concentrations of roughly 1–2 μg L^{-1} (green) occur in the TZ. These low and consistent chl-*a* concentrations combined with anecdotal evidence of residual NO_3^- concentrations in the TZ provided the inspiration for this study to investigate the potential influence of Fe as a bottom-up control on the primary producers in the TZ ecosystem.

The main source of Fe in the cCCS is from continental shelf sediments (Johnson et al., 1999, 2001; Biller et al., 2013; Biller and Bruland, 2013). Iron rich particles are delivered to the ocean via runoff during winter storms and deposited on continental shelf mud belts at depths between 50 and 90 m (Wheatcroft et al., 1997; Xu et al., 2002). Upwelling through the benthic boundary layer (BBL) directly above shelf sediments delivers Fe to the euphotic zone where it can be assimilated by phytoplankton to fuel extensive diatom blooms. A significant source of Fe to the BBL that can be upwelled is the dissolved Fe(II) flux out of the sediments, which is a result of the high rate of organic matter oxidation resulting in reducing conditions just below the sediment–water interface (Elrod et al., 2004). Dissolved Fe(II) concentrations of ~200 μM have been observed in pore waters of these organic-rich, reducing, mud belt sediments (Severmann et al., 2010; Homoky et al., 2012). Iron-binding organic ligands play an important role within the BBL in allowing elevated concentrations of dissolved Fe to occur (Bundy et al., in press). Strong Fe(III)-binding organic ligands can both solubilize leachable particulate Fe and serve to keep Fe(III) from exceeding its solubility and precipitating during the oxidation of dissolved Fe(II) (Buck et al., 2007; Lohan and Bruland, 2008). There is low atmospheric Fe input in the cCCS due to alongshore winds during the upwelling season (Fung et al., 2000; Mahowald et al., 2005), and, as a result, aerosol derived Fe accounts for less than 2% of new production in the cCCS (Mackey et al., 2010). Thus, continental shelf derived external sources of Fe are very important in the cCCS ecosystem.

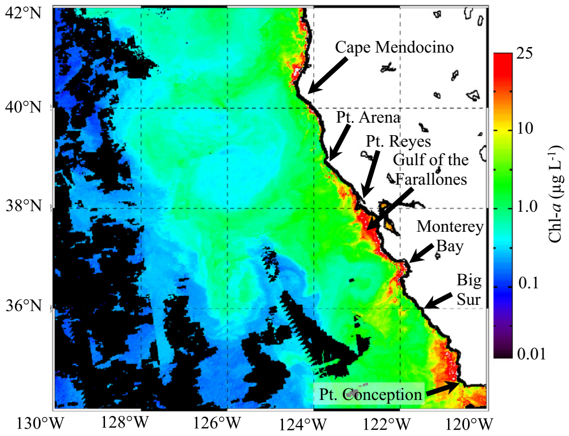

Fig. 1. August 2010 monthly satellite derived surface chl-*a* for the cCCS. The TZ is characterized by relatively low and constant (1–2 μg L^{-1}) chl-*a* throughout the spring and summer.

The width of the continental shelf, in particular the width of the mud belt sediments, along the central California coast impacts the amount of Fe that can be delivered to the surface. Regions with a wider shelf, such as the Gulf of the Farallones, have higher delivery of Fe to the surface than regions with a narrow shelf (Bruland et al., 2001; Chase et al., 2005a; Biller et al., 2013). The delivery of this coastally upwelled Fe to the TZ has widespread implications for the amount of phytoplankton growth that can occur. A seasonal reduction in coastal surface Fe concentrations occurs throughout the spring and summer upwelling season through a combination of reduced upwelling strength later in the season and biological assimilation during the spring and summer (Elrod et al., 2004; Chase et al., 2005b; Biller et al., 2013).

Upwelling of nutrients offshore as a result of curl-driven upwelling or association with cyclonic eddies supplies macronutrients, but very low Fe. These waters will tend towards Fe limitation. Several studies south of Pt. Conception (south of 34°N) in the southern CCS (sCCS) have demonstrated evidence for Fe-limiting conditions, especially in the TZ of the sCCS (King and Barbeau, 2007, 2011). Chavez et al. (1991) observed a decline in diatom blooms within the TZ of the cCCS over the course of their summer study, even though macronutrient concentrations remained elevated. This "demise of the diatoms" was hypothesized to occur due to the progression of the TZ waters into Fe limitation (Chavez et al., 1991); however, no field Fe data was available at the time to support this hypothesis. Carr and Kearns (2003) in a comparison of eastern boundary current systems reported that the cCCS had a low chlorophyll biomass relative to its macronutrient concentrations and suggested that it was perhaps related to the low availability of Fe in this region. Ecosystem control by Fe concentrations in coastal environments has been shown to occur not only in the cCCS (Hutchins et al., 1998) but