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Iron, macronutrients and diatom blooms in the Peru upwelling regime: brown and blue waters of Peru

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Abstract

Surface water transects and vertical profiles for dissolved iron, macronutrients, chlorophyll *a* (Chl *a*), and hydrographic data were obtained in the Peru upwelling regime during August and September 2000. The supply of the micronutrient iron, relative to that of the macronutrients nitrate, phosphate and silicic acid, is shown to play a critical role in allowing extensive diatom blooms to develop in the Peru upwelling system. The extremely high-chlorophyll "brown waters of Peru" (with Chl *a* concentrations between 20 and 45 μg/l) result from massive diatom blooms with maximal photochemical efficiencies (F_v/F_m >0.6) occurring in the iron-rich upwelling region observed over the broad continental shelf off northern and central Peru. The source of the upwelled water in this region is the nutrient-rich subsurface countercurrent in contact with the organic-rich shelf sediments. This subsurface shelf water is suboxic and has extremely high concentrations of dissolved Fe (>50 nM) in the near-bottom waters. In marked contrast, relatively low-chlorophyll "blue waters" (Chl *a* <2 μg/l) with low concentrations of dissolved Fe (<0.1 nM) and high unutilized macronutrient concentrations are observed in the coastal upwelled waters along the southern coast of Peru and in the offshore regions of the Peru Current. Southern Peru is a region without a wide shelf to serve as a source of iron and, as a result, dissolved Fe concentrations in the near-bottom suboxic waters of this region are an order-of-magnitude lower than observed off northern and central Peru. In addition, the offshore Peru Current is a broad, Fe-limited, high-nitrate, lower than expected chlorophyll region extending hundreds of kilometers offshore into the northeast region of the South Pacific subtropical gyre and northwestward into the South Equatorial Pacific.

Keywords: Chlorophyll *a*; Near-bottom suboxic waters; Maximal photochemical efficiencies

1. Introduction

The biological richness of the Peruvian coastal waters is legendary (Brink et al., 1983). Southeasterly trade winds along the coast of Peru result in wind-

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driven coastal upwelling of colder, nutrient-rich subsurface water. Intense upwelling of the macronutrients nitrate, phosphate, and silicic acid to surface waters in this region allows extensive phytoplankton blooms to occur that may extend tens to hundreds of kilometers offshore. Large diatoms tend to dominate the biomass in phytoplankton blooms that develop in these coastal upwelling regimes (de Mendiola, 1981; Wilkerson et al., 2000), and it has been argued that diatom-driven new production efficiently fuels the food chains leading to fish production (Smetacek, 1998). With its year-round, persistent, coastal upwelling, the Peru Current system is one of the most productive marine ecosystems (Barber and Smith, 1981; Carr, 2002), supporting intensive pelagic fisheries, most notably the anchoveta (*Engraulis ringens*; Alheit and Bernal, 1993).

With this rich productivity, it is surprising that high-nitrate, lower than expected chlorophyll (HNLC) conditions have been reported for the Peru upwelling regime. Thomas (1972, 1979) in some of the first discussions of HNLC regimes pointed out that "low-Chl, high-nutrient water is not unique to offshore regions" and that "Off Peru, 'blue' water containing 2 μg Chl/l and 10 μg—at NO_3^-—N/L was found (Strickland et al., 1969)." These authors found it "remarkable" that offshore waters of the Peru Current had not been depleted of nutrients by phytoplankton assimilation. The grazing hypothesis (Walsh, 1976) has been generally accepted as the principle explanation for this observation. It has been suggested that zooplankton are more abundant in the euphotic zone off Peru because of the suboxic water just below, and that this results in more intensive grazing pressure at the beginning of the bloom, keeping the phytoplankton growth under control from the outset (Minas and Minas, 1992). Hutchins et al. (2002), however, recently investigated phytoplankton iron limitation in the high-nutrient Peru Current system and demonstrated that primary producers can be limited by lack of iron in this regime.

It has recently been demonstrated that extensive parts of the California upwelling system are iron limited (Hutchins and Bruland, 1998; Hutchins et al., 1998; Bruland et al., 2001; Firme et al., 2003). Coastal diatoms have high iron requirements (Sunda and Huntsman, 1995; Bruland et al., 2001) that cannot be met by the small amount of iron present with the macronutrients in subsurface oceanic waters (Bruland et al., 2001). The presence or absence of a broad continental shelf can greatly influence the external supply of iron to the upwelled surface waters in coastal upwelling regions (Johnson et al., 1999, 2001; Bruland et al., 2001). Coastal upwelling off central and northern California is most intense in the spring and summer months and this peak in upwelling is temporally out of phase with the river input occurring during the winter months in this semiarid climate. During periods of intense upwelling over a broad shelf, however, the interaction of upwelling water with the shelf sediments can transport elevated concentrations of iron to the surface waters. When upwelling is focused offshore of a narrow continental shelf, the upwelled waters are characterized by low dissolved and particulate iron concentrations, and these waters rapidly develop into coastal upwelling HNLC systems limited by the micronutrient iron (Bruland et al., 2001). Supplemental iron additions to these Fe-limited systems in shipboard grow-out experiments resulted in nitrate drawdown and produced blooms of large diatoms (Hutchins and Bruland, 1998; Hutchins et al., 1998; Firme et al., 2003).

The same physical characteristics that appear to be predictors of Fe-limited areas along the central and northern California coast—intense coastal upwelling, together with a narrow continental shelf and negligible fluvial and eolian inputs of iron—are present in some areas of the Peru upwelling regime. The Peru coast is part of an active continental margin with a relatively narrow shelf, a steep slope and an oceanic trench located just offshore. The width of the continental shelf along Peru varies from 150 km off northern and central Peru to less than 10 km off parts of southern Peru (Fig. 1B). As a result, we predict a mosaic of conditions ranging from iron-replete to iron-limited such as observed off central California (Hutchins et al., 1998; Bruland et al., 2001; Firme et al., 2003). This expectation is supported by historical observations of extremely high Chl *a* concentrations over the northern Peru inner shelf, referred to as the "brown waters of Peru" by Strickland et al. (1969) and by observations of extensive "blue water" regions exhibiting HNLC conditions in the Peru upwelling region (Minas and Minas, 1992).

Coastal Peru has a hyperarid climate with the landscape dominated by remarkably barren hills and