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Editorial

Oceanographic studies in the Humboldt current system off Chile: an introduction

The eastern South Pacific (ESP) Ocean is one of the least explored regions of the global ocean. This vast region holds one of the most productive marine systems in the world, the Humboldt current system (HCS), which includes the coastal upwelling ecosystems off Peru and Chile. Wind-driven upwelling of sub-surface, cold, nutrient-rich and CO_2-saturated waters triggers a significant exchange of heat and gases between the ocean and the atmosphere. In turn, the nutrient input into the euphotic zone enhances the biological production of autotrophs in the surface waters. This production is, to a great extent, transferred through the pelagic web into the large fisheries of the region and/or is exported to the benthic system and ultimately buried in the sediment where it accumulates as organic-rich mud.

Coastal upwelling areas of eastern boundary systems are characterized by strong short-term (days-weeks) and high mesoscale variability in the physical–chemical conditions (Hill et al., 1998). The ecosystems along the ESP also are known to be subject to strong seasonal to inter-annual variability (Barber and Chavez, 1986; Tarazona et al., 1988; Alheit and Bernal, 1993; Thomas, 1999; Hebbeln et al., 2000; Hidalgo and Escribano, 2001; Ulloa et al., 2001). In general, the intra-seasonal variability associated with coastal-trapped waves and the inter-annual variability associated with the El Niño southern oscillation (ENSO) cycle link the HCS with the equatorial Pacific (Enfield et al., 1987; Hormazabal et al., 2001).

The ESP is also characterized by holding one of the most extensive and intense oxygen minimum zones (OMZ) of the global ocean. Off Peru and Chile, these low-oxygen waters constitute the main source of coastal upwelling (Brandhorst, 1971; Blanco et al., 2001; Atkinson et al., 2002). Through the biologically mediated process of denitrification, the OMZ contributes to the global sink of nitrogen in the ocean and acts as a source of the greenhouse gas N_2O to the atmosphere (Codispoti and Christensen 1985; Codispoti et al., 1986). The vertical distribution of the OMZ, whose shallowness can at times impinge on the euphotic layer, is greatly modified by El Niño events, involving a higher oxygenation of the surface and subsurface layers and leading to potentially large changes in ecosystem structure, productivity, trophic transfers, and biogeochemical cycling (Morales et al., 1999; Ulloa et al., 2001). Immediately below the OMZ, lies the Antarctic intermediate water (AAIW), which is considered to be formed mainly at ~55°S (west of southern Chile), and from here to spread to the entire Southern Hemisphere and the tropics. This water mass carries the imprint of global warming and seems to be a sensitive indicator of anthropogenic perturbation, as proposed by climate models (Shaffer et al., 2000).

The responses of the HCS' coastal upwelling ecosystems and adjacent oceanic zones to the various sources of variability, both in space and time, have been poorly analyzed until most recently. Moreover, little else is known about the

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communities inhabiting the OMZ and on the effects of this condition upon the cycling of carbon and nitrogen in the water column and in the sediments. Some of the most important limitations until now have been the lack of long-term time-series studies, comparison and integration of data gathered during different cruises and in different regions of the HCS, and, above all, a short-sight in the need for long-term support of multidisciplinary and multi-approach research in this region. Today, the newly born "Center for Oceanographic Research in the eastern South Pacific (COPAS)", funded by the Fund for Advanced Research in Priority Areas (FONDAP) of the National Commission for Scientific and Technological Research (Lange and Ulloa, 2003), represents a great opportunity and an exciting challenge to overcome all or most of those limitations. This special volume is one step towards achieving the COPAS goals.

This special volume on the physics, biology, biogeochemistry and sediments of the ESP is primarily focused on the HCS off Chile. In this region, at least two large coastal upwelling zones can be identified, based upon their hydrographic and ecosystem characteristics: the northern (18–30°S) and the central–south regions (30–40°S). Upwelling is rather continuous in the north (Shaffer et al., 1999; Blanco et al., 2001), generally displaying low chlorophyll-*a* levels except very close to the coast (Thomas, 1999; Morales et al., 2001), but strongly seasonal (austral spring-summer) in the central-south region (Shaffer et al., 1999; Thomas et al., 2001; Atkinson et al., 2002), with very high chlorophyll-*a* levels ($>10\,\mathrm{mg\,m^{-3}}$) over the wider shelf and shelf break areas during the upwelling period (Ahumada et al., 1991; Thomas, 1999). In both cases, the winds from the south and south-west are favorable for upwelling (see review in Strub et al., 1998).

In this volume, a total of 11 original pieces of research on the HCS off Chile are presented, including the physical and chemical settings, the biological and ecological context in both pelagic and benthic communities, the biogeochemical cycling in the water column and the sediments, together with the recycling, export and sedimentation of organic/inorganic matter, as well as the characteristics of the seafloor environment. Within the physical context, a comprehensive database on all the available hydrographic data for the ESP region off Chile has been compiled by Leth et al.; these authors analyzed three full-depth sections, covering northern, central and southern Chile (along 28, 35, and 43°S, from the coast to 86–88°W), in terms of the general circulation in the region. These results sustain most of previous but sparse observations in the region (i.e. the poleward Peru–Chile undercurrent, with a descending core and peak velocities of $\sim 10\,\mathrm{cm\,s^{-1}}$) and also contribute with new insights such as mechanisms of property transport. The study by Valle-Levinson et al. though more local in nature, deals with one of the poorly known aspects along the Chilean coast, i.e. the wind induced circulation around bays. In this case, short-term hydrographic and velocity observations were analyzed during the upwelling season in terms of wind-induced exchange at the entrance to Concepción Bay (~36°S), in central-south Chile. The circulation pattern revealed a downwind flow in the upper layer being delimited by the pycnocline and upwind flow below, under weak internal friction.

A comprehensive synthesis on the structure and functioning of the HCS ecosystems in the coastal upwelling region off Chile is presented by Escribano et al.; it focuses on the biological and chemical consequences of the 1997–1998 El Niño. Overall, this synthesis proposes a refreshing view of the impacts of ENSO on the HCS ecosystems, neatly summarized in a diagram that contrasts normal to La Niña conditions with El Niño events. The ideas proposed in this study will guide much of our research in the coming years. The bio-optical characteristics and primary productivity during upwelling and non-upwelling conditions in the highly productive coastal ecosystem off Concepción are described in Montecino et al., representing one of the few studies in the region tackling the productivity subject in a functional manner. Cuevas et al. deal with the microbial communities in the same area, also comparing upwelling and non-upwelling conditions in terms of primary and bacterial production, and bacterial and flagellate

abundances; they discuss the relevance of the microbial food web in this upwelling system.

Studies on the vertical flux or export rates in the HCS are scarce but possible due to the existence of a long-term (10 + years) mooring system deployed in the oceanic area off Coquimbo (~30°S; 185 km from the coast; ~4500 m water depth), adjacent to an upwelling center. It includes a sediment trap positioned at ~2300 m water depth. Marchant et al. describe the seasonal and inter-annual variability in the vertical flux of planktic foraminifers in this area, covering the period 1993–1998, and including the 1997–1998 El Niño event, which had only a limited impact on this flux. González et al. summarize the amount and variability in the downward carbon and carbonate fluxes, and identify their main sources (i.e., faecal material and microplankton), during the 1993–1995 period.

Most of our knowledge on the benthic systems and elemental cycling in the sediments in the HCS off Chile derive from studies carried out in the area off Concepción. Gallardo et al. illustrate the effects of the OMZ on the macrobenthic zonation in the shelf and slope, and show that the global hypothesis on diversity and density being lower within the core of an OMZ rather than beneath it in deeper, more oxygenated waters (Rosenberg et al., 1983; Mullins et al., 1985; Wishner et al., 1995) is not valid in this area, but only for diversity. Farías et al. analyze the temporal variability of nitrogen recycling in continental-shelf sediments of the upwelling ecosystem off Concepción. Their results show that the sediments act as a large sink for nitrate here, though the intense denitrification is coupled with nitrification. Complementing this study, Molina et al. describe the benthic nitrogen regeneration processes under the influence of spatial variability in oxygen and organic matter in the sediments off Concepción. As a reflection of the processes occurring in the water column and in the sediments of the HCS region, Muñoz et al. present data on recent sedimentation and mass accumulation rates based on ^{210}Pb along the Peru–Chile continental margin. This study supports the distinction of two main areas within the HCS now based on sedimentation controls, central Peru to northern Chile and central to southern Chile.

Overall, the studies included in this special volume provide an integrated view of the oceanography of the HCS off Chile and adjacent areas and reflect the substantial progress made during recent years in discovering or re-discovering the essentials of this system. No doubt this first volume will serve as a reference for the many scientific problems in the region, old and new, that need to be tackled. Investigations in the HCS should be focused on those essentials that distinguish it from other eastern boundary systems, using new available technologies and multidisciplinary approaches.

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