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Hypoxia in Chilean Patagonian Fjords

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ABSTRACT

Chilean Patagonia is one of the largest estuarine systems in the world. It is characterized by a complex geography of approximately 3300 islands, a total surface area of 240,000 km^2, and 84,000 km of coast line, including islands, peninsulas, channels, fjords, and sounds. The Chilean Patagonia Interior Sea is filled with a mixture of sea, estuarine, and fresh waters, and is characterized by a two layer vertical general circulation. Dissolved oxygen (DO) conditions in these fjords were analyzed based on historic salinity, dissolved oxygen and nutrient data from 1200 oceanographic stations. Horizontal advection of adjacent well oxygenated Subantarctic Waters (5–6 mL L^{-1}) was the mayor source of DO in the deep layers of the Interior Sea. Incoming DO was consumed by the respiration of autochthonous and allochthonous particulate organic matter, as ocean water flows towards the continental fjord heads, reaching near-hypoxic (2–3 mL L^{-1}) or hypoxic levels (<2 mL L^{-1}). As DO declined nutrient concentrations increased towards the fjord heads (from ~1.6 μM PO_4^{-3} and ~16 μM NO_3^- to ~2.4 μM PO_4^{-3} and ~24 μM NO_3^-). Overall, DO conditions in the Interior Sea were mostly the result of a combination of physical and biogeochemical processes. In all eastern channels and fjords, a low DO zone developed near the fjord heads (<4 mL L^{-1}) as a result of larger allochthonous particulate organic matter inputs transported by local rivers. This enhanced organic matter input to the deep layer increased DO consumption due to respiration and overwhelmed the oxygen supplied by horizontal advection. Out of the 90 Chilean Patagonian gulfs, channels and fjords analyzed, 86 systems were oxic (>2 mL L^{-1}) and four hypoxic (<2 mL L^{-1}), but only at their heads. None were found to be anoxic (0 mL L^{-1}). We found these DO conditions to be permanent features of the Chilean Patagonia Interior Sea.

Introduction

The coastal oceans are arguably one of the most important ecosystems on Earth and bear the brunt of the negative effects of human activities on the ocean. The presence of low water column DO concentrations can be a natural condition in many semi-closed coastal systems, such as estuaries and fjords, given their topographic characteristics. This environmental condition, known as hypoxia (DO < 2 mL L^{-1}; Diaz and Rosenberg, 1995), may be produced naturally by the DO consumption associated with high inputs of autochthonous and/or allochthonous organic matter (Zhang et al., 2010). The slow water renewal of semi-closed basins also favors DO consumption due to organic matter degradation (Gray et al., 2002). This situation commonly occurs under the presence of shallow constriction-sills in deep fjords and channels, which slow down or impede deep water circulation (Pickard, 1963, 1971). Anthropogenic activities may also provide additional inputs of organic matter and/or nutrients, which mostly are transported through river basins, or discharged directly into a water body as urban or industrial drainage. Aquaculture is one of such anthropogenic activities, and involves the direct discharge of organic by-products, such as non-consumed food pellets or feces, which may also contribute to generating hypoxic conditions (Holmer et al., 2005; Mulsow et al., 2006; Burt et al., 2012). Hypoxic conditions, and to a greater extent, anoxic conditions, both in deep waters and sediments, can lead to damage for marine biota inhabiting such areas (Kramer, 1987; Breitburg, 2002; Gray et al., 2002). Recently, such areas have been referred to as "dead zones" in the literature (Díaz and Rosenberg, 2008). Dead zones are present worldwide (Díaz, 2001), including some estuaries and fjords (Stanton and Pickard, 1981; Fenchel et al., 1990), and also large areas, such as the Gulf of Mexico, the Baltic Sea and the Black Sea (Zhang et al., 2010).

The Chilean Patagonian Fjords is one of the largest estuarine systems in the world with currently low levels of anthropogenic activity due to the relatively low population density (≈2 inhabitants km^{-2}) and most large towns/cities (Puerto Montt: 176,000

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inhabitants; Punta Arenas: 131,000 inhabitants; Castro: 40,000 inhabitants, Puerto Natales: 20,000 inhabitants; Puerto Aysén: 17,000 inhabitants) are located along the shoreline. Coyhaique, the third largest town in the area (50,000 inhabitants), is located about 120 km from the Aysén Fjord on the border of the Simpson River (116 $m^3 s^{-1}$; Niemeyer and Cereceda, 1984), which is a tributary of the Aysén River. The urban contribution of organic matter appears to be highly localized since there are few cities (i.e., 6 towns/cities 17,000–170,000 inhab.), with large spatial separations between them (500–1000 km).

The main commercial activities in the area are fisheries, aquaculture, and tourism, of which aquaculture is the most important. During 2011 a total of 895 fish and shellfish aquaculture centers were operating, with a total fish and mollusk production of 955,042 ton y^{-1} (SERNAPESCA, 2013). The large quantities of salmon and mollusk farming by-products (uneaten food and/or feces) might have a measurable influence on surface sediment's organic matter content, and therefore on the DO content, due to its consumption during its degradation. Nevertheless, according to Holmer et al. (2005) on Canadian salmon farms, the contribution of organic matter from salmon cages only reaches surface sediments within a 50–100 m perimeter. By means of dispersion models, Cromey and Black (2005) and Stucchi et al. (2005) obtained similar results. An analysis of the effects produced by Chilean salmon farming on the Chiloé–Aysén marine environment concluded that the effects seem to be restricted to the salmon cage shadow, with no broader impact on the ecosystem (Soto and Norambuena, 2004).

The Chilean Patagonian Fjords have only been the subject of oceanographic research during the past 20 years (Silva and Palma, 2008), and the current knowledge on the oceanographic processes associated with water circulation, water and sediment biogeochemistry, and marine biological productivity remains limited. The aims of this study are to perform a comprehensive analysis of water column DO in the Chilean Patagonian Fjords, to define their DO conditions (oxic: $O_2 > 2$ mL L^{-1}; hypoxic: <2 mL L^{-1}; anoxic: $O_2 = 0$ mL L^{-1}) and to infer the processes which may explain these conditions.

Materials and methods

Survey area

The Chilean Patagonia Inland Sea (CPIS) is made up of hundreds of inner channels, sounds, gulfs, and fjords, located between the Reloncaví Fjord and Cape Horn (Fig. 1). It was formed through glacial erosion and tectonic sinking of longitudinal valleys during the Pleistocene (Borgel, 1970; Claperton, 1994), which were then later filled with seawater from the adjacent South Pacific Ocean during the Holocene sea level rise. Thus, the confluence of the seawater and freshwater from rainfall, continental rivers, and glacial melting along the eroded continental border, gave rise to one of the largest estuarine areas in the world. Chilean Patagonia covers an area of approximately 250,000 km^2, with 84,000 km of coastline (continental coastline plus the coastlines of some 3300 islands) (Silva and Palma, 2008). In the CPIS, there are several shallow constriction-sills (0.5–10 km wide; 50–100 m depth), which segment the bathymetry forming isolated deep micro-basins (200–1300 m), and restricting free deep water flow (Fig. 2a, b, e, and f; Sievers and Silva, 2008). The main ones included in this paper are: Desertores, Meninea, Kirke and Carlos III (Fig. 2).

The precipitation in this study area ranges from 1000 to 7000 mm y^{-1} on the western side of the Andes (Niemeyer and Cereceda, 1984). The major fluvial inputs are found in the continental fjords, coming mainly from the larger rivers Petrohué, Puelo, Yelcho, Aysén, Baker and Pascua (Fig. 1; and Table 2), which have nivo-pluvial regimes and respective average annual flows of 284, 676, 363, 628, 1011 and 690 $m^3 s^{-1}$ (DGA, 1988; Niemeyer and Cereceda, 1984; Ríos de Chile, 2013). The discharges from these rivers constitute the major source of freshwater and allochthonous organic matter to the CPIS. The vegetation in this area is predominantly evergreen forest made up mainly of species from the *Nothofagaceae* family (Huiña-Pukios, 2002; Rodriguez et al., 2008).

General water circulation follows a two layer estuarine flow pattern (Sievers and Silva, 2008) with water exchange between the CPIS and the adjacent Pacific Ocean mainly through several narrow and shallow passages located along the adjacent oceanic coastline between the Chacao Channel and Cape Horn (Fig. 1). Occasionally, and associated with wind effects (Caceres et al., 2002) and/or nonlinear tidal effects (Valle-Levinson et al., 2007), a general three layer circulation pattern has also been observed: a thin surface ocean-ward flowing layer, a thick intermediate inward flowing layer, and a thin bottom ocean-ward flowing layer.

Sampling and analyses

Between 1995 and 2012 the Chilean "Cruceros de Investigación Marina en Areas Remotas" program (CIMAR), conducted 16 cruises in the CPIS. Those field campaigns included the sampling of 1161 oceanographic stations, distributed between the Reloncaví Fjord and Cape Horn (Fig. 1, and Table 1). At these stations continuous temperature and salinity records were obtained with a Seabird CTD. Water samples at standard depths for DO and nutrients were taken with a 25 Niskin-Rosette system, between the surface and 10–50 m above the seafloor. All oceanographic stations were performed at the center of the channel or fjord.

The DO was measured according to the Carpenter (1965) technique. Nutrient samples (phosphate, nitrate and nitrite) were stored in acid-cleaned high density plastic bottles (60 mL) and the analyses were done at the Biogeochemical Laboratory of the Pontificia Universidad Católica de Valparaíso by means of a nutrient autoanalyzer according to Atlas et al. (1971). DO saturation values were estimated based on Weiss (1970) algorithm. During CIMAR Fiordos 1, 2 and 3 cruises, pH measurements were performed according to DOE (1994).

At some stations of the CIMAR Fiordos Cruise 15, water samples for nitrous oxide measurements were taken and stored in glass vials (20 mL), which were fixed with 50 μL of $HgCl_2$ and sealed without air bubbles trapped inside. The nitrous oxide analyses were performed at the Oceanographic Laboratory of the Universidad de Concepción by means of a gas chromatographer (VARIAN 3380 with an electro capture detector ^{63}Ni) and the headspace technique according to Mc Ailiffe (1971). Of all the stations that were sampled for nitrous oxide, only one station performed in Almirante Montt Gulf, was included in this study. In this station, called station "P", a CTDO-nutrient cast was performed every 3 h, during a 24-h cycle.

We concentrated our oceanographic analysis on salinity (as a flow tracer *proxy*), DO and nutrients (phosphate and nitrate). Temperature, together with salinity, was used to compute DO saturation and pH was used in the discussion of oceanographic characteristic of station "P". Vertical sections only include depths down to 400 m, which is the most variable portion of the water column. However, in the general circulation schematics, full sections are shown to represent the size and bathymetry of different fjord micro-basins.

From all CIMAR cruises (Table 1), six cross-sections were chosen as being representative of the oceanographic conditions in terms of salinity, DO, phosphate and nitrate. Each of them extended from the adjacent oceanic zone, to the fjord head. For the northern zone, the selected sections were: Boca del Guafo to the Reloncaví Fjord (Section 1); Boca del Guafo to the Puyuguapi Fjord (Section 2); and Boca del Guafo to the Aysén Fjord (Section 3). The central zone