Short communication

Deep ventilation event during fall and winter 2015 in the Puyuhuapi Fjord (44.6°S)

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ABSTRACT. The Puyuhuapi Fjord has previously been reported as one of the hypoxic fjords in Patagonia (dissolved oxygen -DO below 2 mL L^{-1}). Hydrographic sampling between 1995-2015 confirmed hypoxia below 100 m depth, down to the bottom (250 m). A line of sensors at an oceanographic mooring in Puyuhuapi were deployed to continuously record the temporal-vertical behaviour of water column temperature and salinity from the surface down to ~120 m, from February to July 2015. A Multi-parameter water quality sonde was deployed at the bottom of the line, with a DO optical sensor. From February to mid-May, hypoxia was sustained (1.4-1.6 mL L^{-1}). However, from May until the end of June, DO values increased (2.8 mL L^{-1}), exceeding the hypoxia threshold. This was the first event of deep ventilation reported in a Patagonian fjord. During this time period, deep water temperatures increased by ~1.3°C, coinciding with the decreased in salinity from 33.6 to 32.8. The main cause of this event was attributed to the arrival of a new volume of mixed oceanic water into the Fjord, transported by Modified Subantartic Water, with warm temperatures and slightly higher DO values, given its origin in the surface layer of the outer region of the Patagonian fjords and channels.

Keywords: Dissolved oxygen, hypoxia, ventilation, Puyuhuapi, Patagonian fjords, southern Chile.

The Puyuhuapi Fjord (Fig. 1a), has been described as one of the hypoxic fjords in Northern Patagonia, with dissolved oxygen (DO) levels below 2 mL L^{-1} (~30% saturation) between 100-250 m depth (Schneider *et al.*, 2014; Silva & Vargas, 2014). According to these values, deep hypoxia conditions have been attributed to the presence of the southern and northern sills, which impede circulation (Sievers & Silva, 2008; Schneider *et al.*, 2014), and to the input of low-oxygen Equatorial Subsurface Waters (ESSW) (Silva & Vargas, 2014). Generally, DO measurements are carried out using CTD instruments with DO sensors, and by on board chemical analyses with the Carpenter (1965) modification for the Winkler titration method. Since 1995, deep DO values have shown minima of 1.14 mL L^{-1} in the central zone of Puyuhuapi (Silva *et al.*, 1998), with similar records in 2015 (Pérez-Santos *et al.*, 2015). Despite hypoxia having been permanently recorded, DO values have never dropped down to anoxia, indicating that the fjord is ventilated at a certain point in time, keeping the DO levels above 1 mL L^{-1}. In this study, we present the temporal evolution of DO within the hypoxic layer of the Puyuhuapi Fjord, at ~120 m depth. Temperature and salinity was also recorded. The occurrence of a ventilation event that lasted almost a month and a half, is reported.

Deep temperature, salinity, and DO were recorded with a multiparameter probe by YSI, model 6600 V2-4, with hourly temporal resolution. Data were daily averaged to eliminate the influence of semidiurnal tides and other high frequency forcings in the study area (Schneider *et al.*, 2014). The multiparameter probe was installed at a moored oceanographic observation system (44°35.286'S, 72°43.625'W), at ~120 m water column depth (Fig. 1b). In addition to the probe, the line was equipped with HOBO U-20, HOBO U-22 and HOBO U-24 sensors, which allowed the vertical record of temperature and conductivity between 4 February and 12 June 2015 (Fig. 2). In July 2015, the mooring and its instruments were lost, as the result of a strong stormy weather that hit the Puyuhuapi Fjord area.

The vertical time series for temperature displayed the characteristic two-layer structure during summer and autumn (Silva & Calvete, 2002; Pérez-Santos *et al.*, 2014). The first layer (0-10 m) was made up of warm water (13-18°C) from February to mid-April due to the

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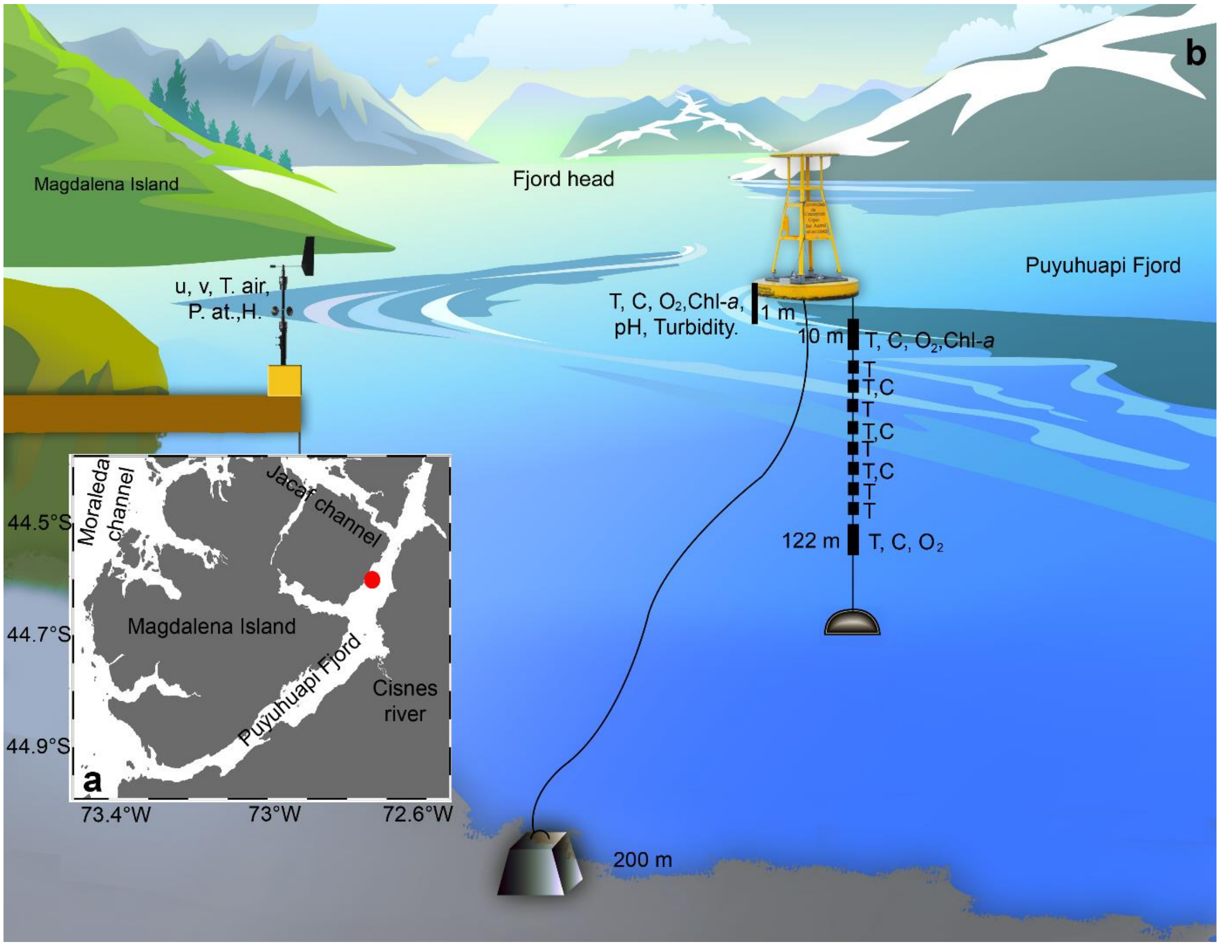

Figure 1. a) Location and b) design of the oceanographic observation system installed in the Puyuhuapi Fjord, Aysén Region. The red circle in a) showed the buoy position. T: temperature, C: conductivity, O_2: dissolved oxygen, Chl-*a*: chlorophyll-*a*, P. at.: atmospheric pression, H: hydrogen.

influence of solar radiation (Fig. 2a). In the second layer (10-120 m), water temperature decreased with depth. From May onwards (autumn), there was cooling of the surface layers due to heat loss. Below the cold surface water, (9-10°C) there was a slightly warmer layer (~11°C) between 20 and 30 m, and temperature then decreased with depth down to ~10°C. The behaviour of the first 50 m of the water column between May and June 2015 was recorded with a CTD in the Martínez Channel (47.8°S), supporting the previously reported subsurface warming via advection of warm oceanic waters (Aiken, 2012; Pérez-Santos *et al.*, 2014). Observing the behaviour of the isotherm 11°C, it can be inferred that in the Puyuhuapi Fjord, the warm water layer is a remnant of summertime warming.

A similar subsurface temperature maximum was also observed and was explained as a remnant of a summertime warming by Silva & Valdenegro (2008), for the 10°C isotherm in the nearby Moraleda Channel during winter 2002. February to March, a deepening of the isotherm down to ~20 m was recorded caused by internal waves. Nevertheless, the most noteworthy result was related to the deepening of the 10°C. This isotherm was located at ~30 m between February and March, and from March onwards, deepened down to 120 m, revealing a warming of deep waters that started at the beginning of the autumn and extended into winter.

The salinity vertical time series displayed a similar behaviour to the temperature time series, during the period of time when deep water temperatures increased (Fig. 2b). Throughout the study period, estuarine water (salinities between 11 and 31, Sievers & Silva, 2008) and the oceanic water mass known as Subantarctic Water (SAAW, salinities between 33 and 33.8; Sievers & Silva, 2008) were detected. SAAW is the principal oceanic water mass that enters Patagonia, with an average temperature of 11.5°C and salinity of 33.8 (Silva *et al.*, 2009).

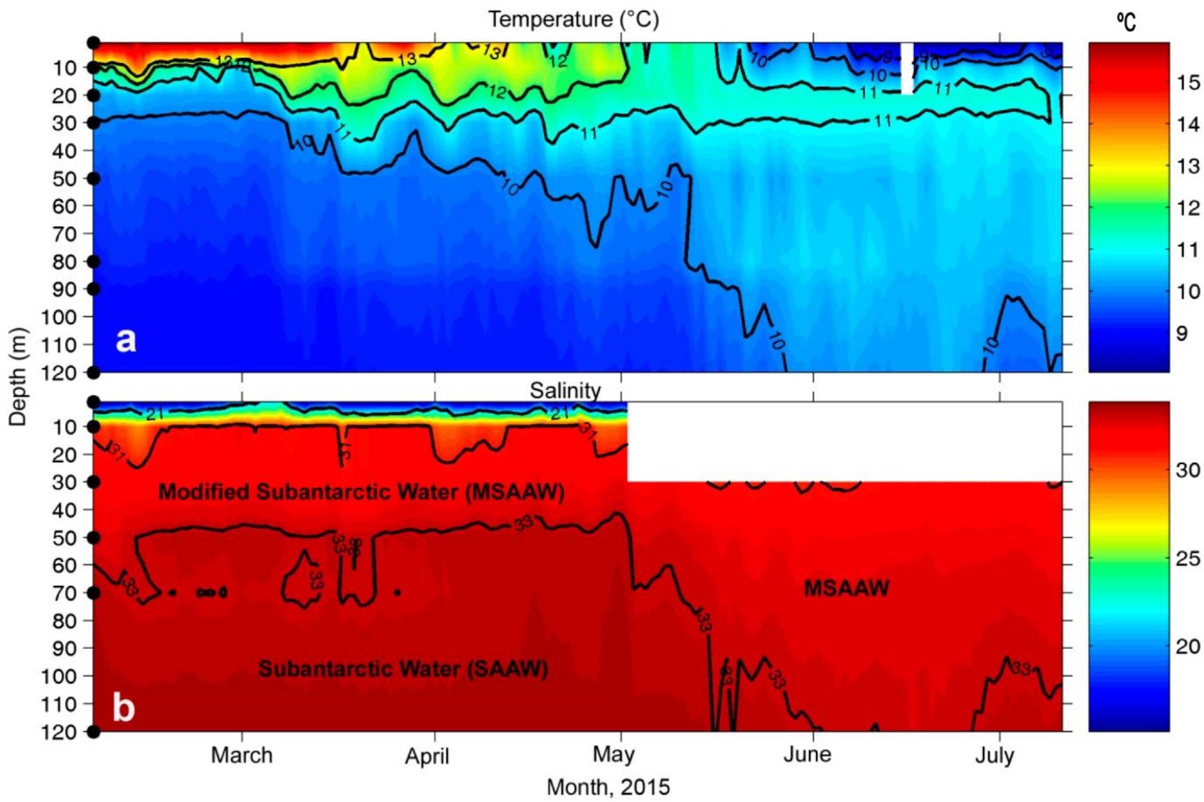

Figure 2. Time series of the vertical distribution of temperature and salinity at the oceanographic buoy installed in Puyuhuapi Fjord from February to July 2015. The black dots represent the vertical position of temperature and conductivity sensors.

This water mass has been recorded down to ~150 depth and transports slightly higher temperatures and higher salinities inside the fjords (Sievers & Silva, 2008; Aiken, 2012; Pérez-Santos *et al.*, 2014). Once inside the fjords, it mixes with estuarine waters (cold and fresh), generating a new water mass, knowns as Modified Subantarctic Water (MSAAW) (Sievers & Silva, 2008).

From February to the beginning of May 2015, vertical salinity structure revealed estuarine and oceanic (SAAW and MSAAW) water masses as horizontal layers, one on top of the other: estuarine water from the surface down to 20 m; then MSAAW down to ~50 m; followed by SAAW down to the bottom. This structure changed during May with SAAW being displaced under 120 m. From mid-May to the end of June, MSAAW dominated the water column between 30 m and 120 m. Hydrographic records obtained from seasonal campaigns in the Martínez Channel (Pérez-Santos *et al*., 2014) and the Puyuhuapi Fjord (Schneider *et al*., 2014) found that the greatest thickness of the MSAAW layer (50 m in the Martínez Channel and 90 m in the Puyuhuapi Fjord) occurred during autumn-winter and not during spring-summer (20 m in the Martínez Channel and 50 m in Puyuhuapi Fjord), when the freshwater input is highest due to ice melt. This suggests the importance of SAAW in mixing and the origin of MSAAW. All previous records, including this study, have shown the presence of MSAAW inside the fjords in subsurface layers. However, in the outer area of Patagonia (the Guafo Entrance), where fjord-ocean exchange occurs, this water mass is in contact with the atmosphere, delimited to the west by SAAW and to the east by estuarine water (Pérez-Santos *et al*., 2014; Fig. 2d).

Figure 3 shows a time series of temperature and salinity, along with DO concentrations and saturation, obtained at ~120 m depth at the head of the Puyuhuapi Fjord. The hypoxia conditions with DO values between 1.4-1.6 mL L^{-1} (saturation between 20% and 25%) were maintained between February and mid-May, in the SAAW layer, with an average salinity of 33.6 ± 0.04 (Figs. 3b-3d), instead of the ESSW layer (salinities above 33.9, Guzmán & Silva, 2002).

This suggests that the origin of hypoxia was low ventilation, as it was proposed by Silva *et al.* (1998) and Schneider *et al.* (2014). Nevertheless, lowest DO values were recorded above the southern sill depth

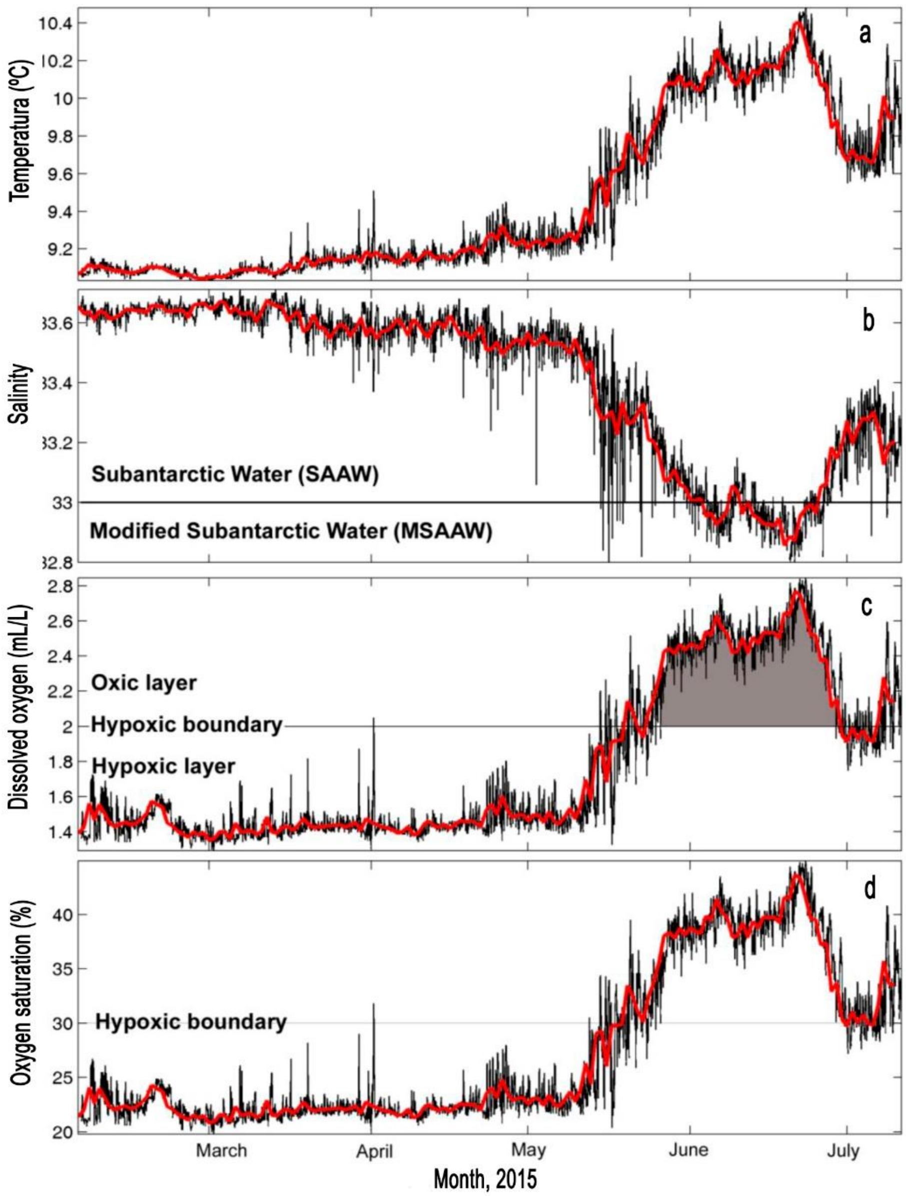

Figure 3. Time series of a) water temperature, b) salinity, c) dissolved oxygen and d) oxygen saturation, obtained at 122 m depth at the oceanographic buoy installed in Puyuhuapi Fjord. The black line represents hourly records and the red line shows the daily average.

(~150 m), which indicates that other processes, such as organic matter remineralization, could be contributing to DO reduction and hypoxia (Silva, 2006). Daneri *et al.* (2012) reported high values of primary production in Puyuhuapi (533 g C m^{-2} $year^{-1}$), comparable with other productive Fjords along the southern coast of British Columbia and the upwelling system off Concepcion, Chile.

As Figure 2 suggests, in mid-May the temperature of deep waters increased to reach maximum values in June. The increase in deep water temperatures was ~1.3°C, coinciding with the decrease in salinity from 33.6 to 32.8 and an increase in DO from 1.5 mL L^{-1} to 2.8 mL L^{-1}, from 22 to 45% (Figs. 3a-3d). Therefore, the DO content of the Puyuhuapi deep waters increased, surpassing the hypoxia threshold, becoming oxic, during this period. This is the first report of ventilation event in a deep layer of a Patagonian fjord. The main cause of this ventilation was the entrance of a new volume of mixed oceanic water mass into the Puyuhuapi Fjord, transported by MSAAW with warm temperatures and slightly higher DO values, due to its origin at the surface of the outer region of fjords and channels of Patagonia (Pérez-Santos *et al.*, 2014).

The temperature of deep waters can be expected to return to normal values in this layer over the course of time (February-April) due to molecular diffusion (Aiken, 2012) and double diffusive layering process (Pérez-Santos *et al.*, 2013, 2014). Studying the periodicity of these events (intensity, duration, etc.) in poorly-ventilated fjords in Patagonia (Silva & Vargas, 2014), will be fundamental in future research for understanding how the deep layer dynamics of this estuarine system behave and their interaction with biogeochemical processes.

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