Progress in Oceanography 129 (2014) 8–18

Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

# On the hydrography of Puyuhuapi Channel, Chilean Patagonia

Wolfgang Schneider [a,b,*], Iván Pérez-Santos [b,d], Lauren Ross [c], Luis Bravo [d], Romanet Seguel [b], Freddy Hernández [e]

[a] Departamento de Oceanografía, Universidad de Concepción, Campus Concepción, Víctor Lamas 1290, Casilla 160-C, código postal: 4070043, Concepción, Chile
[b] Centro COPAS Sur-Austral, Universidad de Concepción, Campus Concepción, Víctor Lamas 1290, Casilla 160-C, código postal: 4070043, Concepción, Chile
[c] Department of Civil and Coastal Engineering, University of Florida, Gainesville, FL 32611, USA
[d] Centro de Estudios Avanzados en Zonas Áridas (CEAZA), Facultad de Ciencias del Mar, Universidad Católica del Norte, Coquimbo, Chile
[e] Programa de Postgrado en Oceanografía, Facultad de Ciencias Naturales y Oceanográficas, Universidad de Concepción, Casilla 160-C, Concepción, Chile

ARTICLE INFO

*Article history:*
Available online 24 March 2014

ABSTRACT

This work describes the hydrographic conditions found in Puyuhuapi Channel (northern Chilean Patagonia) during recent years on a seasonal scale. Puyuhuapi Channel was once a glacial valley, but the retreating ice allowed the inflow of marine waters. Five surveys were conducted between 2008 and 2012; historical data from 1995 to 2007 were included. A meteorological/oceanographic buoy was also installed in the northern section of Puyuhuapi Channel and was operational beginning on April 12th, 2011. Puyuhuapi Channel's surface characteristics highlight a fresher northern part and a more haline southern part except during winter when the pattern can reverse due to the intrusion of oceanic water via Jacaf Channel. The channel exhibits a highly variable meridional and seasonal vertical stratification, especially in its northern part where during spring and summer the water column is highly stratified but partially mixed during winter. Puyuhuapi Channel is the only fjord/channel with severe hypoxic conditions in all of Chilean Patagonia.



## Introduction

The austral fjords and channels of southern Chile (Chilean Patagonia) constitute an significant portion of the earth's inner fjords and extend from 41°S to 56°S, occupying an approximate area of 240,000 km$^2$ (Pantoja et al., 2011). Their hydrography is usually characterized by a vertical two-layer structure with a highly variable 5–10 m freshwater surface and a more uniform saltier lower layer (Silva and Calvete, 2002; Dávila et al., 2002; Sievers, 2008). Sievers and Silva, 2008, classified the surface layer in three categories according to the contribution of different freshwater sources: (1) Estuarine freshwater with salinities <11 PSU; (2) Estuarine-brackish water with salinities between 11 and 21 PSU and (3) Estuarine-saline water with salinities ranging from 21 to 31 PSU. Sub-Antarctic Water (SAAW, temperature ~11.5 °C and salinity ~33.8, (Silva et al., 2009)) usually occupies the first 150 m of the water column following the freshwater surface layer. At the interface of both layers lineal mixing takes place resulting in Modified SAAW (MSAAW) with salinities between 31 and 33 PSU (Sievers and Silva, 2008). Remnants of Equatorial Subsurface Water (ESSW), related to Subtropical Underwater, with high salinity (34.9 PSU), temperature of 12.5 °C and low dissolved oxygen (⩽2.0 mL L$^{-1}$) (Wyrtki, 1964; Chuecas and Ahumada, 1980; Silva et al., 2009), are carried poleward by the Günther Current (also known as the Peru–Chile undercurrent) and enter the southern fjords and channels at subsurface depths (150–300 m) as long as is allowed by the sill distribution (Brandhorst, 1971; Silva, 1983; Sievers and Silva, 2008). Hence, water masses present in fjords and channels of southern Chile can be identified by salinity alone.

The fjords and channels of Aysén, Patagonia (43°–47°S) are highly heterogeneous and show strong seasonal variability in local mixing rates and nutrient and light supplies (Montecinos et al., 2004). Puyuhuapi Channel, Aysén, was once a glacial valley, but the retreating ice allowed the inlet of marine waters. The channel stretches from Puyuhuapi village in the north (44°19′S, 72°33′W) to Moraleda Channel in the south (44°57′S, 73°21′W) which connects it to open seas. The channel is united with open seas via the Jacaf Channel in the north (Fig. 1), unlike the other fjords and channels of Chilean Patagonia. The bathymetry of both channels is rather complex, with variable bottom depths up to more than 400 m thus dividing the channels into several basins. A sill of about 170 m is located just north of the Uspallante River and another one

* Corresponding author at: Departamento de Oceanografía, Universidad de Concepción, Campus Concepción, Víctor Lamas 1290, Casilla 160-C, Concepción, Chile. Tel.: +56 41 2661235.

*E-mail addresses:* wschneid@udec.cl (W. Schneider), ivanperez@udec.cl (I. Pérez-Santos), laurenross13@me.com (L. Ross), lubravo@udec.cl (L. Bravo), rseguel@oceanografia.udec.cl (R. Seguel), freddyhernandez@udec.cl (F. Hernández).

http://dx.doi.org/10.1016/j.pocean.2014.03.007
0079-6611/

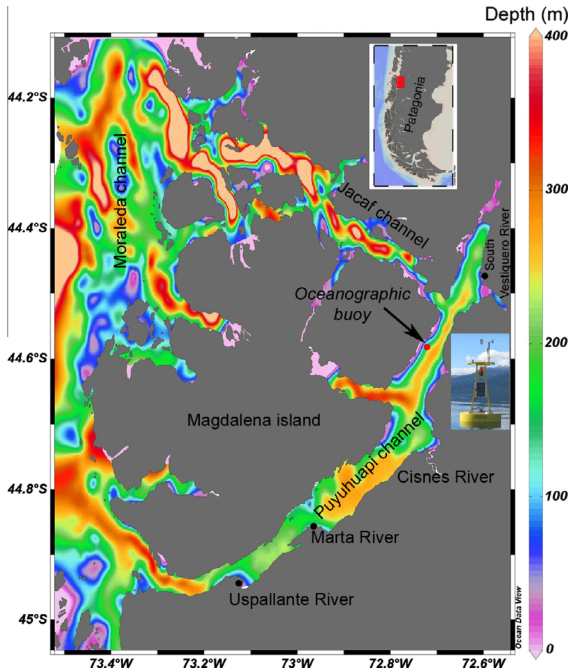


**Fig. 1.** Map of the study area. Continent and islands are shown in grey. For the various channels of the region, their bathymetry is color shaded; colors are related to ocean depth via the color code on the right. The position of the meteorological/oceanographic buoy is marked by a red dot the inlay depicts the above surface portion of the buoy. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of less than 100 m is close to the head of Jacaf Channel (Fig. 1). Puyuhuapi Channel receives freshwater discharges from the Cisnes River (218 $m^3 s^{-1}$ annual mean river flow), which empties into Puerto Cisnes Bay (located in the middle of the channel) from the south after 160 km of run-off length; the Ventisquero River (~40 $m^3 s^{-1}$ annual mean river flow, Fig. 1), numerous creeks, and rain fall (⩾2000 mm per year) constitute other sources of fresh water (Calvete and Sobarzo, 2011).

As with other southern fjord areas, Puyuhuapi-Jacaf Channels have been affected by intense salmon farming activity over the last 20 years and by occasional outbreaks of harmful algae blooms (Seguel et al., 2005; Molinet et al., 2003). Salinity and temperature variations play an important role in the proliferation of viruses, diseases and parasites, e.g. *Caligus rogercresseyi*. This parasite grows and develops better in environments with salinity >15 PSU and temperature of ~10 °C thus creating substantial mortality in salmon fish farms (~30%) (Furci, 2009). Hence, knowledge of the horizontal–vertical distribution of salinity and temperature contributes to the sustainable management of aquaculture farming in the region.

No detailed (long-term) oceanographic data exist for this zone. This work attempts to describe the hydrographic conditions found in Puyuhuapi Channel during recent years on a seasonal scale which among might be helpful to understand the connectivity between outer and inner waters and within inner waters, so as to better place fish farms along the channel. We expect that the special bathymetry of the channel (sills in the south and in the north), one main fresh water source (the Cisnes River), along-channel winds, and the two connections with oceanic waters produce highly variable stratification in space and time and a low-oxygen environment.

## Data

New dense hydrographic surveys were conducted in austral spring 2008, austral summer 2009, austral spring 2010, and austral winter 2011 and 2012 in Puyuhuapi and Jacaf channels (for station density refer to Table 1 and Fig. 4) (from here on: seasons always refer to those in the southern hemisphere). At each station, CTD casts were carried out down to 100 m depth during the Puyuhuapi-I and Puyuhuapi-II campaigns and close to the bottom otherwise. Both channels were sampled during 4 days and during about the same tidal phase. Hydrographic profiles were obtained with a Seabird 25 CTD equipped with additional oxygen and fluorescence sensors. Data processing followed Seabird recommendations and one-meter averages were obtained. Three additional hydrographic transects passing through both channels were carried out by the Chilean National Oceanographic Commission between 1995 and 2003 (CIMAR-Fjord cruises) and their hydrographic profiles, on standard depth resolution, were included here in the water mass and dissolved oxygen analyses. The horizontal spacing of the hydrographic profiles was somewhat coarser but included oceanic stations (Table 1 and Fig. 8).

**Table 1**
Oceanographic campaigns carried out in Patagonian fjords and channels.

| Expeditions | Date | Stations | Sampling area |
|---|---|---|---|
| CIMAR-1 | 8/10–11/11/1995 | 99 | Northern Patagonia (41.5°/46.5°S) |
| CIMAR-2 | 16–19/10/1996 | 102 | Central Patagonia (46.5°/51.7°S) |
| CIMAR-4I | 26/9–9/10/1998 | 34 | Northern Patagonia (41.5°/46.5°S) |
| CIMAR-3 | 9–23/10/1998 | 60 | Southern Patagonia (51.7°/55.6°S) |
| CIMAR-4II | 25/2–8/3/1999 | 37 | Northern Patagonia (41.5°/46.5°S) |
| CIMAR-7I | 7–21/7/2001 | 72 | Northern Patagonia (41.5°/46.5°S) |
| CIMAR-7II | 12–27/11/2001 | 47 | Northern Patagonia (41.5°/46.5°S) |
| CIMAR-8I | 1–26/07/2002 | 50 | Northern Patagonia (41.5°/46.5°S) |
| CIMAR-8II | 15–28/09/2002 | 39 | Northern Patagonia (41.5°/46.5°S) |
| CIMAR-9I | 12/08/2003 | 32 | Northern Patagonia (41.5°/46.5°S) |
| CIMAR-9II | 9/11/2003 | 27 | Northern Patagonia (41.5°/46.5°S) |
| CIMAR-10I | 17/08/2004 | 50 | Northern Patagonia (41.5°/46.5°S) |
| CIMAR-10II | 8–26/11/2004 | 46 | Northern Patagonia (41.5°/46.5°S) |
| CIMAR-11I | 16–27/07/2005 | 71 | Northern Patagonia (41.5°/46.5°S) |
| CIMAR-11II | 11–21/11/2005 | 70 | Northern Patagonia (41.5°/46.5°S) |
| CIMAR-12I | 8–24/07/2006 | 48 | Northern Patagonia (41.5°/46.5°S) |
| CIMAR-12II | 3–13/11/2006 | 56 | Northern Patagonia (41.5°/46.5°S) |
| CIMAR-13I | 30/07/2007 | 44 | Northern Patagonia (41.5°/46.5°S) |
| CIMAR-13II | 2/11/2007 | 47 | Northern Patagonia (41.5°/46.5°S) |
| CIMAR-14 | 19/10/2008 | 32 | Central Patagonia (46.5°/51.7°S) |
| Puyuhuapi I | 14–17/11/2008 | 35 | Northern Patagonia (41.5°/46.5°S) |
| Puyuhuapi II | 27/02/2009 | 29 | Northern Patagonia (41.5°/46.5°S) |
| CIMAR-15 | 10/2009 | 39 | Southern Patagonia (51.7°/55.6°S) |
| Puyuhuapi III | 14/11/2010 | 44 | Northern Patagonia (41.5°/46.5°S) |
| Puyuhuapi IV | 9/09/2011 | 44 | Northern Patagonia (41.5°/46.5°S) |
| Puyuhuapi V | 27–29/9/2012 | 24 | Northern Patagonia (41.5°/46.5°S) |
| | Total | 1281 | |

A meteorological/oceanographic buoy was installed in the northern section of Puyuhuapi Channel (Fig. 1 and 44°35.3′S and 72°43.6′W) and was operational beginning on April 12th, 2011 (http://sur-austral.udec.cl/productos/series-de-tiempo-canal-puyuhuapi/), although several data gaps existed. Wind speed and direction, sea surface temperature, and salinity data from the buoy were employed in this study. The meteorological data were collected at ~2.5 m above sea level with a temporal resolution of 3 min and the oceanographic data were registered at ~1 m depth each hour (Fig. 1, see buoy picture). Recently two additional meteorological stations were installed in the southern Puyuhuapi Channel (44°54.95′S and 73°01.65′W, February 2013) and in the central part of Jacaf Channel (44°19.436′S and 72°53.858′W, April 2013) (Fig. 2d). These stations were equipped with the same wind speed and direction monitors as in the meteorological/oceanographic buoy (Young 05106 model with speed and direction precision of 0.3 $m s^{-1}$ and ±3°, respectively).

A pressure gauge was installed at shallow depths in the northern part of Puyuhuapi Channel close to the buoy from September 9th to December 13th, 2012, with 10 min of temporal resolution