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Double-diffusive layering and mixing in Patagonian fjords

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ABSTRACT

Double-diffusive layering was quantified for the first time in the Chilean Patagonian fjords region (41.5–56°S). Approximately 600 temperature and salinity profiles collected during 1995–2012 were used to study water masses, quantify diffusive layering and compute the vertical diffusivity of heat. Development of "diffusive-layering" or simply "layering" was favored by relatively fresh–cold waters overlying salty–warm waters. Fresh waters are frequently derived from glacial melting that influences the fjord either directly or through rivers. Salty waters are associated with Modified Subantarctic (MSAAW) and Subantarctic Water (SAAW). Double-diffusive convection occurred as layering in 40% of the year-round data and as salt fingering in <1% of the time. The most vigorous layering, was found at depths between 20 and 70 m, as quantified by (a) Turner angles, (b) density ratios, and (c) heat diffusivity (with maximum values of 5×10^{-5} m^2 s^{-1}). Diffusive-layering events presented a meridional gradient with less layering within the 41–47°S northern region, relative to the southern region between 47° and 56°S. Layering occupied, on average, 27% and 56% of the water column in the northern and southern regions, respectively. Thermohaline staircases were detected with microprofile measurements in Martinez and Baker channels (48°S), showing homogeneous layers (2–4 m thick) below the pycnocline (10–40 m). Also in this area, increased vertical mixing coincided with the increased layering events. High values of Thorpe scale ($L_T \sim 7$ m), dissipation rate of TKE ($\varepsilon = 10^{-5}$–10^{-3} W kg^{-1}) and diapycnal eddy diffusivity ($K_\rho = 10^{-6}$–10^{-3} m^{-2} s^{-1}) were associated with diffusive layering. Implications of these results are that diffusive layering should be taken into account, together with other mixing processes such as shear instabilities and wind-driven flows, in biological and geochemical studies.

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Introduction

Double-diffusive convection (DDC) produces convection in a wide variety of fluids (Schmitt, 1994). It contributes to vertical mixing of the water column (You, 2002; Mack and Schoeberlein, 2003), as well as to thermohaline circulation and heat transport (You, 2002). When hydrodynamically stable water masses overlay each other, and the quantity of heat and salt within these layers vary, the process known as double-diffusive convection occurs as an attempt to restore equilibrium. In other words, double diffusive convection occurs in response to differences in molecular diffusion rates between heat and salt as heat diffuses approximately 100 times faster than salt (Schmitt, 2001). If heat or salt are unstably distributed within the water column, potential energy is released from the unstable component through molecular diffusion. Therefore, double diffusive convection develops in the water column when the slopes of vertical gradients of temperature and salinity have the same sign.

When both temperature and salinity decrease with depth, which is characteristic of latitudes where evaporation dominates over precipitation, double diffusive convection occurs as "salt-fingering" or "finger regime". And when both temperature and salinity increase with depth, as is typical of high latitudes where precipitation dominates over evaporation, double diffusive convection is defined as "diffusive-layering" (Kelley et al., 2003) or simply "layering," as will be called from hereon. When cold fresh water sits on top of warm salty water (conditions favorable for layering), heat from the lower layer is transferred to the colder upper layer by the release of potential energy from the temperature field. This is an overcompensating restoring force, which

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produces defined layers of well-mixed fluids separated by marked density gradients (Schmitt, 1994; You, 2002; Kelley et al., 2003). Typically, the top of the water column of Patagonian fjords is cold and fresh because of melting glaciers, and because of input from river discharge and precipitation.

Early evidence of double-diffusive mixing in the ocean was found through the development of simultaneous staircase structures in vertical profiles. Schmitt (1981) described double diffusive convection for the Tyrrhenian Sea (west of Italy), the Mediterranean outflow into the eastern Atlantic, and the subtropical underwater in the western subtropical Atlantic. In studies of the Tyrrhenian Sea, mixed layers exceeded 50 m, whereas in the other two cases they were approximately 10 m. Cascading isothermal layers, with thicknesses ranging from 2 to 10 m were reported for the Arctic Ocean by Neal et al. (1969). Staircase-like layers can be together or be separated by perturbations within the water column (e.g., internal wave). The absence of a well-defined vertical staircase does not indicate that DDC is not present (Farmer and Freeland, 1983).

The global atlas of DDC (You, 2002, based on the 1994 Levitus climatological atlas of the open oceans) shows that this process is favorable in 44% of the oceans, of which 30% is salt fingering and 14% is layering. The occurrence of salt fingering was associated with the Central Waters where evaporation exceeds precipitation, such as the case around Easter Island (Moraga and Valle-Levinson, 1999). But salt fingering also develops with relatively warmer and saltier deep waters overlying colder and fresher Antarctic Bottom Water. In high latitudes, where surface cooling and ice melting are ubiquitous, such as in the polar and subpolar Arctic and Antarctic regions (e.g., the Gulf of Alaska, the Okhotsk, Labrador and Norwegian Seas) layering occurs (You, 2002). Evidence for the occurrence of layering in a Patagonian channel was presented by Pérez-Santos et al. (2013) in the form of a staircase structure, with layer thickness between 2 and 5 m, within a vertical profile of temperature and salinity.

The fjords region of Patagonia extends from 41°S to 56°S, occupying an approximate area of 240,000 km^2, which represents the region with the largest extension of fjords in the world (Fig. 1). Freshwater input in this region consists of river fluxes ($27.8 \times 10^3\ m^3\ s^{-1}$) and rain ($33.5 \times 10^3\ m^3\ s^{-1}$) (Dávila et al., 2002). The hydrography of this system is characterized by a vertical structure of two layers in temperature and salinity (Silva and Calvete, 2002). The cooler and fresher surface layer in the first few meters of the water column (5–10 m) is more variable than the bottom layer. This variability occurs at different scales and is caused mainly by fluctuations in solar radiation, freshwater inputs (rivers, rain, glacial ice melt and coastal runoff), advection of water to and from channels and vertical mixing by wind and tide (Silva and Calvete, 2002; Dávila et al., 2002; Sievers, 2008). However, the vertical distribution of warmer temperature and higher salinity in the deep layer tends to be much less variable than near the surface.

Water masses have been described in the fjords and channels of Patagonia by Sievers (2008) and Sievers and Silva (2008) on the basis of salinity values only. Estuarine water (EW, cold–fresh water) was identified in the first few meters of the water column, formed by the contributions of rivers and summer-time glacier ice melting. The EW included Estuarine Salty Water (ESW, salinity between 21 and 31 g/kg) and Estuarine Fresh Water (EFW, salinity between 11 and 21 g/kg), while the waters with salinities less than 11 g/kg were classified as Fresh Water (FW) (Sievers and Silva, 2008). Below ESW, Subantarctic Water (SAAW, salinity >33 g/kg) was described extending to approximately 150 m. Mixing between ESW and SAAW result in Modified SAAW (MSAAW) with salinities between 31 and 33 g/kg. Equatorial Subsurface Water (ESSW) extended from ~150 m to ~300 m, followed by Antarctic

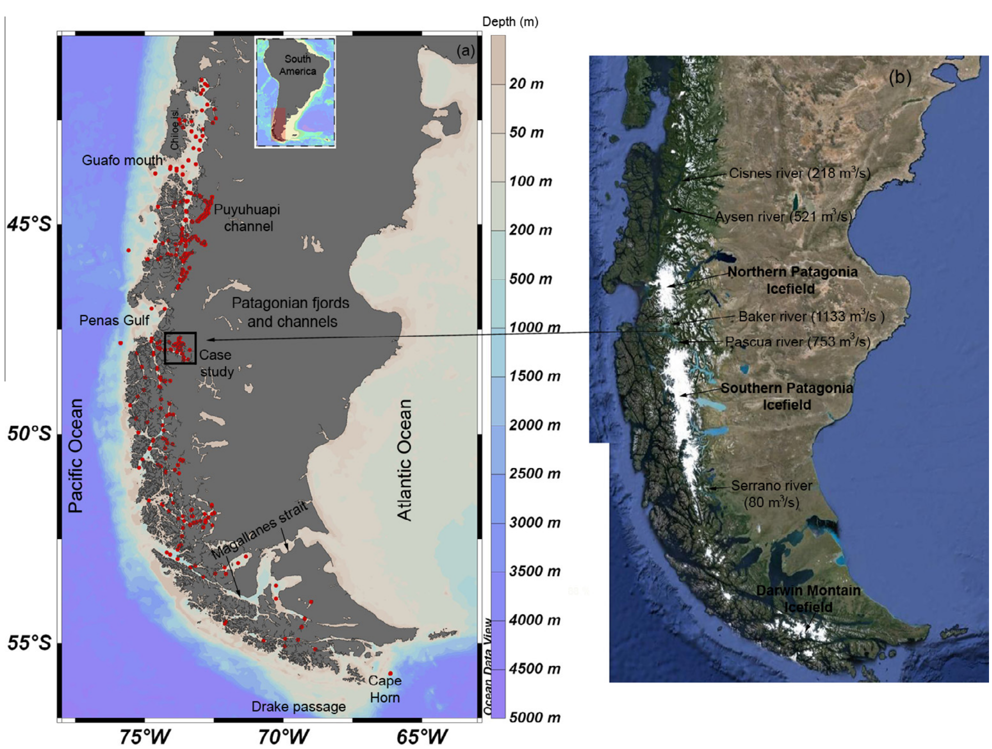

Fig. 1. (a) Study area and distribution of hydrographic stations. Details regarding expeditions are listed in Table 1. (b) The main freshwater supply in the Patagonian fjord region, highlighting the Northern and Southern Patagonian Icefield and the most important river. Reference of river discharge was extracted from Meerhoff et al. (2013) to Baker and Pascua rivers, from Calvete and Sobarzo (2011) to Aysén and Cisnes rivers and from Dávila et al. (2002) to the Serrano river.

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