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4.1. Water masses and circulation in austral Chilean channels and fjords

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Chile's austral channel and fjord region, located approximately between 41.5º and 55.0º S, has received more and more attention from the Chilean scientific community, as reflected in the increased number of research cruises and publications. Before the start of the CIMAR Program in 1995, oceanographic studies were scarce, sporadic, and limited in their observations. The first systematic observations were done during the Swedish expedition Lund University-Chile (1948-1949) carried out between Puerto Montt and Canal Moraleda (Brattström & Dahl 1951) and the Canadian expedition Hudson-Chile 70 (March 1970) carried out from Puerto Montt to Seno Almirantazgo. Although the information from this cruise was analyzed by Pickard (1971, 1973), this author used the data mainly to compare the oceanographic characteristics of Canadian and Chilean interior waters. Later, Silva *et al.* (1995) used the temperature, salinity, and dissolved oxygen data obtained during the Hudson-Chile 70 expedition to perform an oceanographic analysis of the channels, sounds, and gulfs located between Puerto Montt and Laguna San Rafael. Guerrero (2000) carried out a similar study in the area from Golfo de Penas to Strait of Magellan.

Seasonal cruises were also carried out in Fiordo Aysén between 1991 and 1992 (Sievers & Prado, 1994), and in some channels of the Magallanes region (Celio, 1991; Panella *et al.*, 1991; Antezana, 1999). Data for the adjacent Pacific Ocean zone are provided by some oceanographic stations from the Hudson-Chile 70 and Piquero (1969) expeditions and were analyzed by Silva (1978) and Silva & Neshyba (1977, 1979/1980).

The results of the CIMAR-Fiordos cruises from Puerto Montt to Laguna San Rafael (northern zone; 100 stations), Golfo de Penas to Strait of Magellan (central zone; 90 stations), and Strait of Magellan to Cape Horn (southern zone; 51 stations) describe the chemical and physical characteristics, water masses, and the circulation in this extensive region (Silva *et al.*, 1997, 1998; Silva & Calvete, 2002; Sievers *et al.*, 2002; Valdenegro & Silva, 2003).

The data was used to identify the water masses present in the adjacent oceanic area and interior waters, and to propose schematic models of general circulation patterns based on the distribution of the water's physical and chemical characteristics. T-S diagrams were used to identify water masses present in the oceanic area adjacent to the austral channel region (Silva & Neshyba, 1979/1980; Sievers & Nowlin, 1984; Silva *et al.*, 1995, 1997; Sievers *et al.*, 2002; Valdenegro & Silva, 2003). Three water masses were detected adjacent to the northern zone, between the surface and 800 m depth: Subantarctic Water (SAAW) up to 150 m depth; remnants of Equatorial Subsurface Water (ESSW) between 150 and 300 m depth; and Antarctic Intermediate Water (AAIW) below 300 m depth. An analysis of the central zone off Golfo de Penas, up to 800 m depth, showed SAAW between the surface and 150 m depth; a core of ESSW between 200 and 300 m depth; and AAIW with its core around 600 m depth. To the south, in the area of Golfo Trinidad, ESSW was not observed (Sievers *et al.*, 2002), although a salinity maximum was detected that was not associated with the typical ESSW oxygen minimum. Silva & Neshyba (1979/1980) attributed this salinity maximum to the Western Pacific Subsurface Water (WPSSW) advecting from the west. In the southern zone, Sievers & Nowlin (1984) identified SAAW up to 150 m depth and below this, the Modal Subantarctic Water (MSAAW) described by McCartney (1977), which varied in thickness from 300 to 700 m. Below the MSAAW, at depths exceeding 1,000 m, was the AAIW, followed by the Circumpolar Deep Water (CDW) at even greater depths.

The first two of these water masses penetrate into the region through the surface (SAAW) and subsurface (ESSW) layers, spreading as far as the bathymetry of the gulfs and channels allows them. The SAAW mixes with fresh water (FW) in different proportions, according to the contributions from rivers, glaciers, coastal runoff, pluviosity, and the distance or proximity of the FW sources. Silva *et al.* (1998) used the mixing triangle method to estimate the mixing of SAAW with FW in the channels and fjords and the rate at which ESSW penetrates into the interior waters. When the ESSW is not present, a lineal mixing process takes place between SAAW and FW. The water resulting from this process with salinities between 31 and 33 psu is known as Modified Subantarctic Water (MSAAW) and the lower-salinity water as Estuarine Water (EW). In turn, a three-category classification was also proposed according to the levels of participation in the estuarine mixture. Estuarine-saline water is over 66 % sea water (21-31 psu); estuarine-brackish water is 33-66 % sea water (11-21 psu); and estuarine-fresh water is less than 33 % sea water (2-11 psu).

The vertical distribution of the oceanographic water characteristics indicates a general two-layer structure. The upper layer reaches a depth of 20-30 m in the northern and central zones (Sievers & Prado 1994; Silva *et al.*, 1995, 1997; Sievers *et al.*, 2002) and 50-75 m in the southern zone (Valdenegro & Silva, 2003). Strong vertical gradients (pycnocline, oxycline, nutricline) generally separate the upper layer, where the characteristics are more variable, from the deep layer, where the vertical distribution tends to be more uniform.

The distribution of the water's physical and chemical characteristics acts as integrators, through which the direction of the net flow can be inferred. Silva *et al.* (1995, 1998), Sievers et al. (2002), and Valdenegro & Silva (2003) used this information to propose schematic models of vertical circulation for some channels and fjords (Figs. 1a to 1d).

The first general circulation models were proposed for the northern zone based on the data analyzed from the Hudson-Chile 70 cruise (Fig. 1a; Silva *et al.*, 1995), including the flow of estuarine waters towards the ocean and the penetration of oceanic waters into the channel region, both for vertical and horizontal circulation. This proposition was validated during the CIMAR 1 Fiordos cruise and the proposed models were also applied to some nearby channels from this region.

Silva *et al.* (1998) used the distribution of the observed water characteristics to separate the general horizontal circulation into three levels, thereby offering a simple representation of the net or residual circulation (Figs. 2a-2c). The first level corresponds to the surface layer (between 0 and 20-30 m depth), the second to the intermediate layer (30-150 m), and the third to the bottom layer (from 150 m to the bottom). As the surface layer of EW moves out from fresh water sources and approaches the ocean, its salinity increases and it flows away from the channels and fjords (Fig. 2a). The intermediate layer of SAAW enters Golfo Corcovado through Boca del Guafo, where it is modified to MSAAW due to mixing with fresher surface waters. It then splits into two branches: one flowing north as far as Seno Reloncaví and the other flowing south as far as Estero Elefantes (Fig. 2b). The ESSW entering the third level also comes through Boca del Guafo. Its displacement to the interior region is limited by the submarine topography. This water mass occupies only the deep areas (> 150 m) of the southern part of Golfo Corcovado and the channels Jacaf, Puyuguapi, and Moraleda up to the Meninea constriction-sill (Fig. 2c).

The western ends of the oceanic channels south of Chiloé are shallow due to the shallow sill running along the upper edge of the continental platform. Therefore, ESSW cannot flow into these channels (Fig. 2c). Moreover, these channels are narrow, relatively deep, and contain many islands, all of which hinder the exchange of waters between the ocean and the central channel (consisting of Moraleda, Errázuriz, and Elefantes channels) and, therefore, with the adjacent continental channels (Figs. 2a and 2b).

Vertical circulation in the northern zone is marked by two important constriction-sills that block the flow of water, namely Paso Desertores-Apiao (<100 m) between the Ancud and Corcovado gulfs and Meninea constriction-sill (<50 m) in Canal Moraleda. Although they are not the only obstacles interfering with the free movement of the waters, they are the shallowest sills when compared with those separating Golfo Ancud from Seno Reloncaví or the 120-m-deep submarine range located north of Meninea constriction-sill.

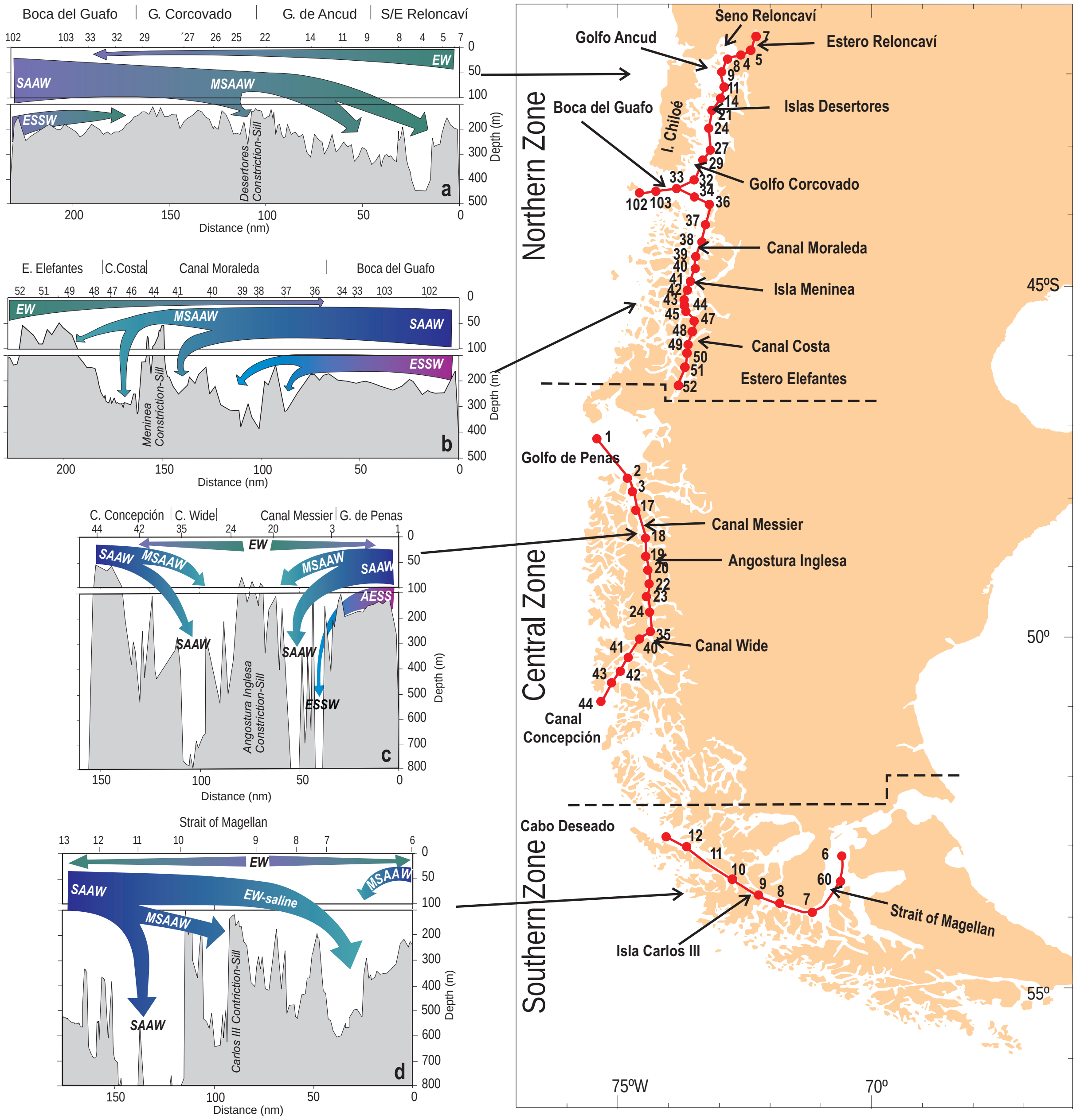

Figure 1: Schematic vertical circulation model for: a) Boca del Guafo to Estuario Reloncaví; b) Boca del Guafo to Estero Elefantes; c) Golfo de Penas to Canal Concepción; d) Strait of Magellan (adapted from Silva *et al.*, 1998; Sievers *et al.*, 2002; Silva & Valdenegro, 2003).

Perhaps the greatest importance of these topographic features is that they restrict or impede the passage of ESSW, with low dissolved oxygen content, towards the microbasins to the north or south, thereby permitting the flow of MSAAW mixed with EW over the submarine range. Once on the other side, this mix sinks and fills the microbasins with waters rich in dissolved oxygen (Figs. 1a and 1b). This circulation allows the ventilation of the microbasins and avoids the reduction of the dissolved oxygen content to quasi-anoxic or anoxic levels in the channels and fjords.

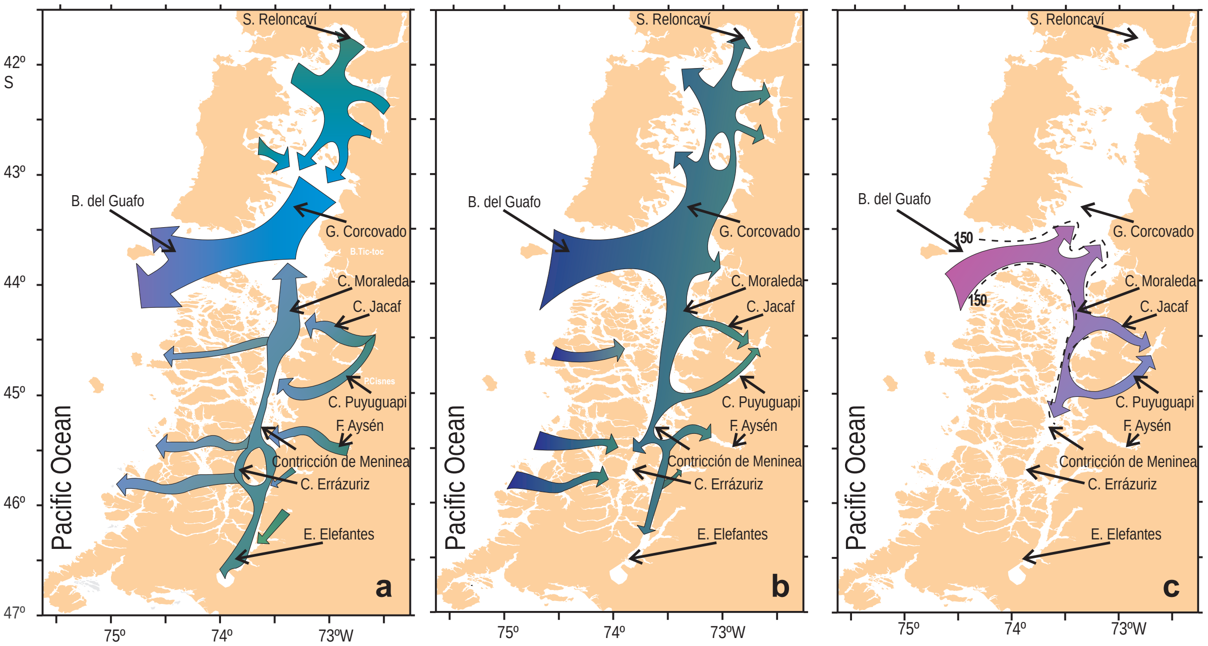

Figure 2: Schematic horizontal circulation model by layers: a) surface (0- ~ 30 m); b) intermediate (~ 30 - ~ 150 m); c) deep (~ 150 m to the bottom) (taken from Silva *et al.*, 1998).

An interesting "damming" situation occurs in Canal Messier, in the central zone. The Angostura Inglesa, a constriction-sill only 80 m deep, divides the channel into two separate microbasins, the northern one over 1,300 m deep and the southern one over 750 m deep (Fig. 1c). The characteristics of the water filling these microbasins indicate that, even though it is all SAAW, the water in each basin has a different origin and, due to the "dam effect" of the Angostura Inglesa, these two waters do not mix. The northern microbasin is filled with SAAW coming from depths between 50-150 m that enters Canal Messier through Golfo de Penas, and the southern microbasin is filled with SAAW that enters through the Trinidad and Concepción channels and crosses over the shallow sill (75 to 100 m deep) adjacent to the continental shelf (Sievers *et al.*, 2002). The different geographic origins of these waters can be seen in their different characteristics; the southern waters are warmer and have more dissolved oxygen, but lower salinity and density values.

The vertical circulation scheme proposed for this channel (Sievers *et al.*, 2002) indicates that, north of the Angostura Inglesa constriction-sill, net surface (0-50 m) flows are produced in which EW moves to the ocean through Golfo de Penas; the same is true south of Angostura Inglesa but the water moves through the Wide and Concepción channels. In turn, water from Golfo de Penas penetrates the northern microbasin of Canal Messier. South of Angostura Inglesa, the intermediate layer (50 to 75-100 m) of the Wide and Messier channels are filled with MSAAW through the Trinidad and Concepción channels; below this layer, these channels are filled with SAAW to the bottom of the microbasins. On the other hand, ESSW also penetrates the Messier microbasin. Its penetration, given the relatively low depth of Golfo de Penas, is deemed to be occasional and dependent on favorable oceanographic and meteorological conditions (Fig. 1c) (Sievers *et al.*, 2002; Palma & Silva, 2004).

In the southern zone, the Strait of Magellan is divided into three microbasins: an eastern microbasin between the Atlantic mouth and Segunda Angostura, a central microbasin between Segunda Angostura and Isla Carlos III, and a western microbasin from Isla Carlos III to the strait's western mouth (Fig. 1d). In general, the water masses in the fjord and channel system of the Magallanes region are Pacific Subantarctic Water (PSW), Atlantic Subantarctic Water (SAAW), and Fresh Water (FW). The mixture of the latter two forms EW and MSAAW (Valdenegro & Silva, 2003).

The vertical circulation scheme proposed by Valdenegro & Silva (2003) considers, in the Strait of Magellan, a net surface flow of EW from the central area of the strait towards both the Pacific and the Atlantic oceans. The subsurface layer, in turn, has a net flow of SAAW from the Pacific to the Atlantic, which flows over the coastal sill of the western mouth, sinking below the surface layer as it moves into the strait. This water mixes with FW to form EW and MSAAW in the upper 150 m. The western microbasin is filled with SAAW below 150 m. The constriction-sill (about 100 m deep) located off Isla Carlos III acts as a physical barrier that impedes the entry of MSAAW and SAAW from the Pacific into the central microbasin. However, the estuarine-saline water (EW-saline), located between 75 and 100 m depth, passes over the constriction-sill, sinks in the central microbasin due to its higher density, and fills the deep area with EW-saline (Fig. 1d). This causes a difference between the water masses or bodies filling both microbasins. The western microbasin contains EW in the upper layer (< 75 m), MSAAW in the intermediate layer (75-150 m), and SAAW in the deep layer (> 150 m), whereas the central microbasin contains EW-saline throughout the entire vertical column (Valdenegro & Silva, 2003). The water flowing from the Atlantic Ocean does not seem to have a great influence on the central basin of the Strait of Magellan. Rather, it mainly affects the eastern microbasin, where the entry and exit flows are regulated by tides (Valdenegro & Silva, 2003).

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