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3.1. Temperature and salinity in the austral Chilean channels and fjords

Hellmuth A. Sievers
Facultad de Ciencias del Mar y de Recursos Naturales. Universidad de Valparaíso.
E-mail: hellmuth.sievers@uv.cl

Before the start of the CIMAR Program in 1995, oceanographic research in Chile's austral interior waters (between approximately 41.5º and 55.0º S) was scarce, sporadic, and limited. The most important of these studies were those carried out by the Swedish expedition Lund University-Chile (1948-1949) between Puerto Montt and Canal Moraleda (Brattström & Dahl, 1951); the Canadian expedition Hudson-Chile 70 (March 1970) between Puerto Montt and the Strait of Magellan (Pickard, 1971, 1973; Silva *et al.*, 1995; Guerrero, 2000); seasonal cruises in Fiordo Aysén between 1991 and 1992 (Sievers & Prado, 1994); and cruises in the channels with international traffic of the Magellan region (Celio, 1991; Panella *et al.*, 1991; Antezana, 1999).

The CIMAR Fiordos cruises contributed data for this large austral region, which was divided into three zones: the northern zone, from Puerto Montt to Laguna San Rafael (CIMAR 1 Fiordos; 100 stations); the central zone, from Golfo de Penas to Strait of Magellan (CIMAR 2 Fiordos; 90 stations); and the southern zone, from Strait of Magellan to Cape Horn (CIMAR 3 Fiordos; 51 stations) (Fig. 1). The results of these cruises describe the physical and chemical water characteristics, water masses, and circulation in this region. Silva *et al.* (1997, 1998), Sievers *et al.* (2002), Silva & Calvete (2002), and Valdenegro & Silva (2003) analyzed the temperature (T) and salinity (S) characteristics gathered during these cruises. Based on these results, the characteristics and vertical temperature and salinity structures of the interior austral waters are described.

The vertical temperature distribution (T-Z) shows, in general, a two-layer structure. In the upper layer, the temperature is variable with maxima and minima resulting from the action, either individual or combined, of different factors. These thermal forcing factors include annual fluctuations in solar radiation, contribution of warmer or colder waters from rivers and glaciers, precipitation (rain, snow, hail), coastal runoff, vertical mixing due to wind, advection of oceanic waters, and possibly geothermal warming. Occasionally a strong vertical gradient or thermocline separates the surface layer from the deep layer, where the temperature distribution tends to be more uniform, at times, almost isothermal. The upper layer is up to 20-30 m deep in the northern zone, 50-100 m deep in the central zone, and 50-75 m deep in the southern zone.

Pickard (1971), Silva *et al.* (1997), and Silva & Calvete (2002) studied the various temperature vertical distributions in order to determine their structure and position in the austral channels and fjords and to identify the associated forcing factors that interact, to a greater or lesser degree, in the production of the different T-Z types. Thus typical profiles were generated that could be used to deduce the forcing factors based on the profile type and without the need to know the area's entire thermal structure. Silva *et al.* (1997, 2002) analyzed the vertical thermal structure of each oceanographic station located in the northern (Tables Ia and Ib in Silva *et al.*, 1997) and central zones (Table Ia in Silva *et al.*, 2002). These authors identified and created schemes to represent 11 vertical structures of temperature (Fig. 2).

In types T1 and T2, the surface layer is warmer than the deep layer and a mixed layer may or may not form. The temperature decreases monotonically to the bottom and does not present any inversions, which are usually the result of surface warming produced by annual fluctuations in solar radiation. Surface mixing due to wind forcing generates the mixed layer that is present in the T2 structure.

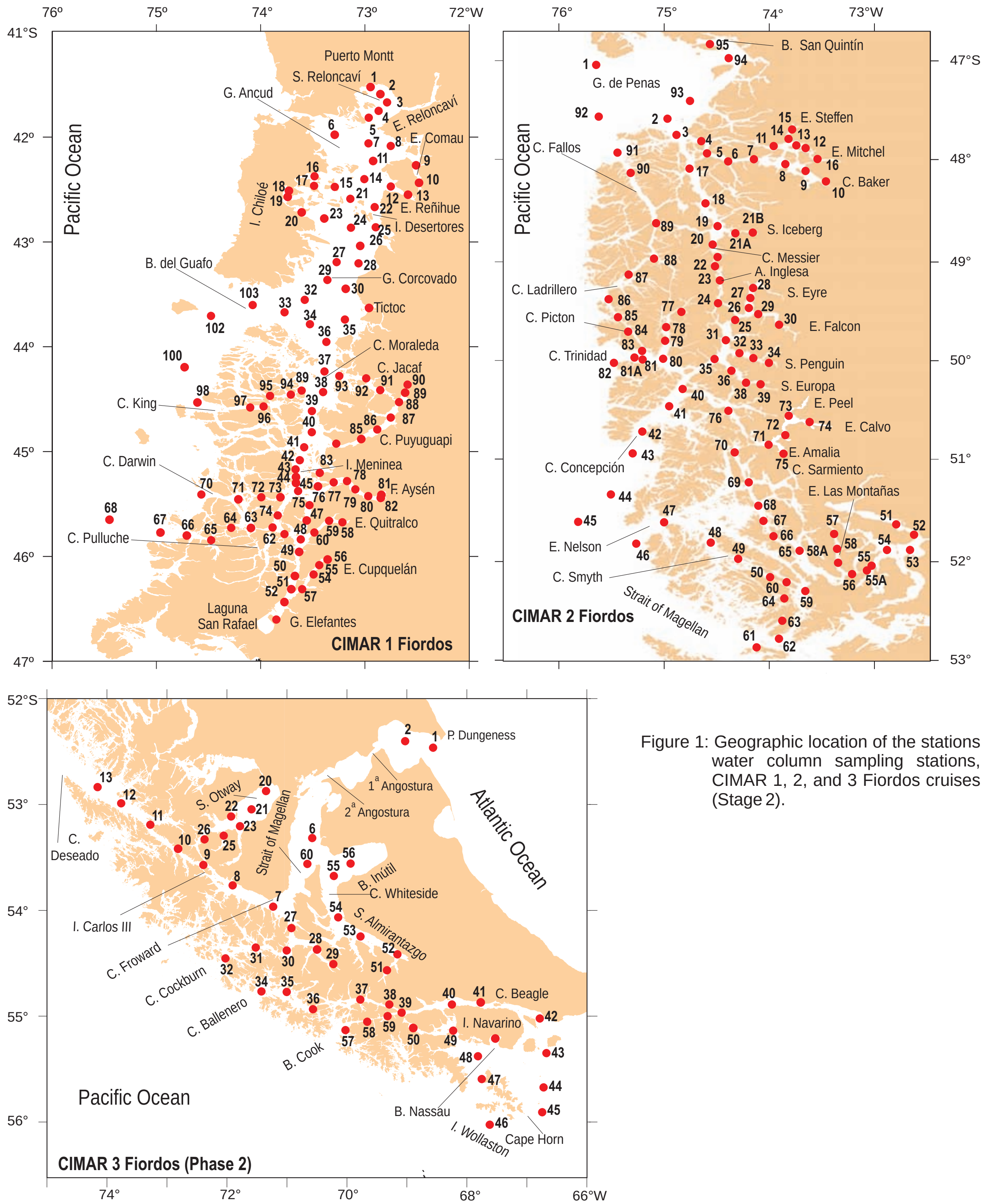

Figure 1: Geographic location of the stations water column sampling stations, CIMAR 1, 2, and 3 Fiordos cruises (Stage 2).

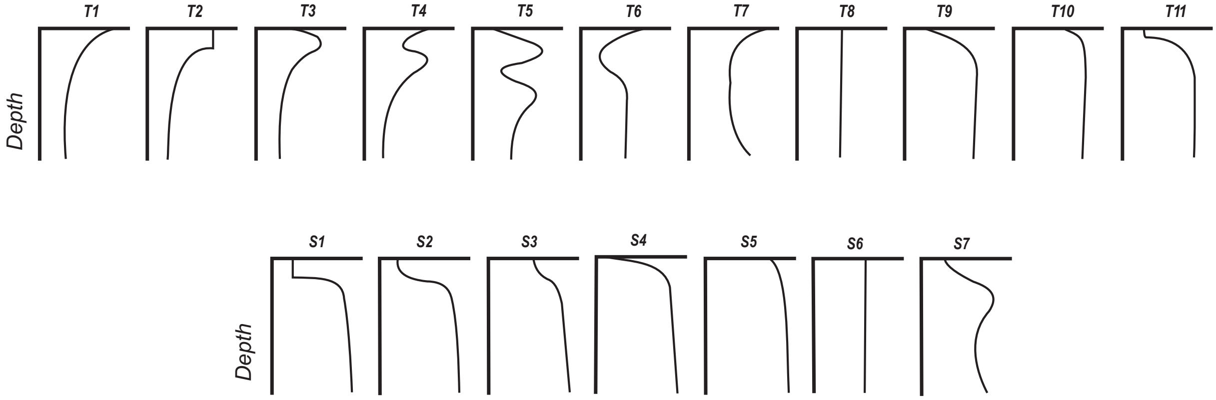

Figure 2: Schematic representation of the different types of vertical temperature (T) and salinity (S) structures proposed for the Chilean austral channels and fjords (adapted from Silva *et al.*, 1997, 2002).

Types T3, T4, T5, and T6 are characterized by one or more temperature minima or maxima in the water column. This indicates that, besides the warming or cooling of the surface layer, other forcing factors such as the advection of cooler external waters are causing these inflections. The T3 structure is observed where an initial T1 or T2 structure receives fluvial discharges with relatively low temperatures. The T4 structure occurs when most of the surface layer of an initial T3 structure is warmed. The temperature rises in the first meters, causing a sub-surface minimum. This is followed by a preexisting relative maximum and a deep remnant of type T1 or T2.

The T5 structure is mainly associated with glaciers and is the result of multiple individual or collective forcing factors such as local warming, cold fresh water contributions, and the advection of comparatively warmer waters from the central channels, which mix, forming different maxima and minima. The T6 structure is characterized by a sub-surface minimum and a warmer deep layer. Sievers & Prado (1994) proposed the advection of warm waters from geothermal sources in Fiordo Aysén but, since no anomaly was detected in the chemical characteristics of the near-bottom water, they proposed as an alternative the renewal of deep waters as originating from the adjacent channels.

The T7 structure is basically characterized by increased temperatures towards the bottom resulting from initial T1 and T2 structures that are disturbed at intermediate or deep depths by an external forcing factor. This could be advection of colder water at intermediate levels; the penetration of warmer, denser water at deep levels; or warming caused by hydrothermal and/or heat transference sources through conduction from a warm bottom (hot spot). This does not necessarily contradict the previous statements, since thermal vents are found in several sectors that could provide enough heat to increase the temperature in the area adjacent to the bottom.

Strong vertical mixing generates the T8 structure, a practically isothermal column reaching, in some intermediate deep areas (100-150 m), to the bottom. The T9 structure results from winter cooling and/or the contribution of cold fluvial or glacial water to a quasi isothermal water column. Depending on how intense the cooling is, an inverse thermocline may be generated, followed by a more homogeneous deep layer. This thermal inversion can be maintained as long as the salinity of the surface layer is low enough to compensate the increase in density that is produced by the decreased temperature that prevents the cold water from sinking. Thus, a stable vertical structure is established that permits the existence of the inverted thermocline.

The T10 structure is derived from a T9 type structure in which the surface temperature increases due to local warming. The T11 structure also originates in a T9 structure but, in this case, the surface minimum is maintained and a small mixed layer is formed, probably due to wind action.

The T-Z structure sequence observed in the different channels, fjords, and gulfs results from progressive mouth-to-head changes, that is, from more oceanic conditions, where the main forcing factor is solar radiation, to estuarine conditions, where colder fresh waters are usually contributed in winter and warmer waters in summer. In this sequence, some intrusion effects of the deeper waters tend to be superimposed on the intermediate levels, which have different thermal characteristics, thereby generating relative minima and maxima in the water column. For example, between the oceanic area and Golfo Reloncaví (Figure 14a in Silva *et al.*, 1997), the vertical thermal structure gradually changes from a normal T2 structure with a relatively deep mixed layer in the oceanic area (~ 50 m) to a T8 structure in the Golfo Corcovado area, where the mixed layer comprises all the water column (~100-150 m); a T1 structure is then observed in Golfo Ancud and, finally, a T7 structure in Seno Reloncaví.

Although Valdenegro & Silva (2003) did not propose a similar classification with the data obtained in the southern zone, they also reported a predominantly two-layer temperature structure. In most of the analyzed channels, the cold, variable surface (< 75 m) generated inverted thermoclines of variable intensity that could be categorized as T10. In some shallow areas (< 70 m), the thermal structure was quasi homogeneous, resulting from vertical mixing produced by the area's typical strong winds and tides and the absence of a thermocline and/or halocline. The resulting highly unstable water column can be categorized as a T8 structure. The deep water (> 100 m) in the interior channels tended, in turn, to be quasi isothermal at all the analyzed stations.

The vertical salinity distribution, like that of the temperature, presents a general two-layer structure. In this case, a surface and a deep layer are separated by a halocline whose intensity depends on the surface salinity values. Salinity is low in the surface layer (15-20 m), reaching values below 1 psu in extreme conditions such as those at the head of Fiordo Aysén (Sievers & Prado, 1994; Silva et al., 1997). Salinity usually increases in the deep layer, which stretches from under the halocline to the bottom. However, on some occasions, conditions that were almost isohaline were observed in deep waters.

Pickard (1971), Silva *et al.* (1997), and Silva & Calvete (2002) grouped the different vertical distributions of salinity versus depth (S-Z) into seven structures; these are represented schematically in Figure 2. The forcing factors acting on these structures are basically the presence of sea water and the contribution of fresh water from rivers, precipitation, coastal runoff, and glaciers. These structures, to greater or lesser degrees, are generated by the surface layer interactions between sea water and fresh water and vertical mixing due to the joint action of the wind and the deep advection of saltier waters. As with temperature, Silva *et al.* (1997, 2002) analyzed the vertical salinity structures at each oceanographic station observed during the CIMAR 1 and 2 Fiordos cruises. The results of these classifications are published in Tables 1a and 1b of Silva *et al.* (1997) for the northern zone and 1b of Silva *et al.* (2002) for the central zone.

Fresh water is important in these structures, as it forms the S1, S2, and S4 structures, which have salinities lower than 25 psu in their upper layers (Pickard, 1971; Silva *et al.*, 1997; Silva & Calvete, 2002). Although fresh water here does not dominate the mixture ($\geq$25 %), its influence is still noticeable, especially when considering the very small volume contributed by rivers as compared to the sea water. The interior water zones that have salinities higher than 25 psu are considered to be S3 or S5 structures, depending on the case.

Wind, along with the fresh water contribution, is a forcing factor in the S1 structure. The effect of the wind increases turbulence, generating the characteristic surface mixed layer of this structure. The S6 structure is associated with a deep mixed layer that is produced by wind forcing in some shallow or intermediate depth areas (up to 150 m, a depth that sometimes reaches the bottom). Nevertheless, the mixing produced by the wind does not seem to be the only explanation for this case, which could also be related to the possible penetration of less saline and more homogeneous water from a lateral channel.

The S7 structure, observed in the oceanic zone, consists of a low salinity surface layer resulting from the contribution of less saline, interior waters. Salinity then increases between 150 and 300 m due to the advection of remnants of the more saline Equatorial Subsurface Water. This is followed by a less saline layer originating in Antarctic Intermediate Waters and centered at 600 m depth (Silva & Neshyba, 1979-1980).

The S1, S2, and S4 structures show strong haloclines that, either alone or reinforced by thermoclines, produce strong pycnoclines. These structures are generally predominant in the continental channel region, where the fresh water contribution is important. The density gradients complicate or impede vertical mixing by reinforcing the two-layer structure. In the oceanic channels, where salinity is higher due to the proximity to the sea and the contribution of fresh water is lower, haloclines are weaker and the S3, S5, and S6 structures predominate.

Although Valdenegro & Silva (2003) did not prepare a similar classification from the information obtained during the CIMAR 3 Fiordos cruise in the southern zone, it can be deduced from their work that no new S-Z structures were detected and that the same structures described above for the northern and central areas are also found in this area.

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