PERSPECTIVES ON INTEGRATED COASTAL ZONE MANAGEMENT IN SOUTH AMERICA
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THE ESTUARINE SYSTEM OF THE AYSÉN FJORD

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1 INTRODUCTION

Chile's austral region from 41°S to 55°S corresponds to one of the planet's most complex system of fjords and channels, forming some of the largest estuarine systems of the world (Palma, 2004). In Chile, this system has a length of over 1600 km, and a surface area of nearly 240,000 km^2, with a high degree of geomorphologic and hydrographic complexity.

The coastline of southern Chile (below 41°S) is comprised of a continuous series of deep basins, channels and islands formed by glacial erosion during the Quaternary and tectonic sinking of the Central Chilean Valley. This area extends from Puerto Montt City (42°30'S) to Cape Horn (55°58'S), in a rugged region composed by a myriad of islands, fjords and channels with a relief ranging from 500 to 2000 m (Silva 2002). The bottom topography of the inlets is made irregular by frequent sills, which act as barriers for the circulation of bottom waters, favoring high sedimentation and a depression in dissolved oxygen, although anoxia is never attained (Silva, 2002). These factors, plus highly variable climatic conditions and minimal anthropogenic influence (Silva 2002), produce ecosystems that can be considered structurally and functionally unique (Palma 2004).

The Aysén fjord is located in the middle of this exceptional territory (45°12'S), with a length of 65 km, and an average width of 6.5 km (Fig. 1). The fjord was formed during the Holocene by glacial erosion, it's western part connect with the ocean through the Costa and Moraleda channels, with a median depth of 217 m and a maximum inner depth of 350 m. The fjord mouth opens in a "v" shape that contains a group of small islands. The inner part is almost isolated from direct oceanic influence, with the exception of the ocean driven deep flow (see below); its surface waters receive freshwater discharges from the Condor (50 m s^{-1}), Cuervo (100 m s^{-1}) and Aysén (500-1000 m s^{-1}) rivers (Guzman, 2004). Its main circulation forcings are: coastal ocean semidiurnal tides, local wind stress and river discharges.

The Aysén climate is influenced by polar and sub-polar winds year round, generating the humid (oceanic) characteristic of the western side of the Andes at these latitudes. The annual precipitation pattern shows a strong meridional gradient with 4000 mm yr^{-1} on the west side of the fjords to less than 600 mm yr^{-1} in the east side, along the border with Argentina. The average atmospheric annual temperature of the area is between 7°C and 9°C, with maximum values in January ($\approx$18°C) and minimum ($\approx$2°C) in July.

The physical, chemical and biological oceanography of the Chilean fjord system has been, and continue to be, the main focus of the CIMAR-Fiordos program, coordinated by the Chilean National Oceanographic Committee (Silva and Palma 2005). This research program organized and deployed 8 scientific cruises to the Chilean fjords between 1995 and 2004, five of which

collected information in the area of the Aysén fjord. All CIMAR-Fiordos data can be requested online (free of charge) at the website of the Hydrographic and Oceanographic Service of the Chilean navy (http://www.shoa.cl). Most scientific articles related to this area have been published (in spanish) in the scientific journal "Ciencia y Tecnología del Mar, Chile" (available online at: http://www.cona.cl).

2 HYDRODYNAMICS

The overall dynamics of an estuary, and its steady state salinity distribution, depend on two variables: R, the volume of freshwater that enter from the rivers during one tidal period and V, the tidal prism which corresponds to the volume brought into the estuary by the tide and removed over each tidal cycle. Depending upon the relationship between these two variables, estuaries can be grouped into classes (e.g. salt wedge, inverse, intermittent, highly stratified, etc.). Fjords correspond to highly stratified estuaries, where the R/V ratio fluctuates between 0.1 and 1.0. The Aysén fjord is characterized by a slow circulation, with a surface outflow layer, less than 10 m thick, of 0.03 m s^{-1} and an interior compensatory flow of 0.05 m s^{-1} (Cáceres et al. 2002). These characteristics generate residence times inside the fjord in excess of 500 days (Guzmán, 2004). Indeed, other authors have suggested residence time of the order of 10 months at the entrance of the Aysén fjord (Salinas and Hormazábal, 2004). Although the classical estuarine circulation is a two-layer system, Cáceres et al. (2002) have proposed that the Aysén fjord may behave as a three-layer system depending on wind conditions. Coastal tides represent one of the most important forcings in the area. The tidal wave is mixed semidiurnal, with minimum difference (<2 m) between high and low tides (Fierro et al. 2000).

The fjord, in terms of conservative variables such as salinity and temperature, can be divided in two layers separated by a halocline (vertical gradient of 6 psu/10m) that in its inner part reaches down to 25 m. Below the halocline salinity increases up to 31.4 psu (Silva et al. 1997, Guzmán and Silva 2002). Temperature in the fjord fluctuates between 9°C and 11°C, but at any given time it may be vertically homogeneous.

3 WATER QUALITY: OXYGEN AND NUTRIENTS DYNAMICS

Fjords' surface waters are well oxygenated through the year (6.0-8.2 ml l^{-1}), with maximum values in spring near the head of the fjord, mainly caused by the seasonal increase in primary production (see below). Consequently, nutrients (nitrate and phosphate) are low through the year with minima during spring. In deeper waters, oxygen doesn't show significant seasonal variability, even though the sub-surface minimum changes from 50 m during summer to more than 100 m in spring (Guzman 2004). Below 100 m dissolved oxygen shows a stable behavior through the year (Guzman and Silva 2002). Nutrients also show seasonal variations in the location of sub-surface maxima following the oxygen dynamics.

Along its main axis the Aysén fjord shows important deep water quality differences. For example, deep water oxygen can be higher than 5 ml l^{-1} at the fjord's mouth and lower than 3

ml l^{-1} at its head (Guzmán and Silva 2002). Nevertheless, deep waters near the head of the fjord have not been reported as anoxic.

Nutrient studies show that some of them have higher concentrations at inland fjords compare to those closer to the ocean. For example, Prado-Fiedler (2000) has shown that ammonium can reach subsurface (10 m) values above 2 μmmol l^{-1} near the head of the Aysén fjord. However, other nutrients such as nitrate and phosphate do not show large horizontal differences but a clear vertical structure. In the case of the Aysén fjord, nitrate and phosphate are located mostly below the halocline with a clear oceanic origin (Guzmán and Silva 2002). This has been corroborated by studies of the Aysén watershed that shows that the Aysén River can be classified as oligotrophic (Oyarzo 2006).

Aysen Fjord's water profiles show very steep vertical gradients for the main nutrients: phosphate, nitrate, nitrite and silicate. While deep waters remain with relative constant values through the year, upper layers (>20 m) show large variations between seasons, been mainly modulated by phytoplankton blooms during spring and by freshwater discharges in winter season (Guzmán and Silva 2002).

4 FJORD'S ECOLOGY

Based on available information from the oceanographic cruises Cimar- Fiordo 1, 4 and 7, Aysén Fjord's phytoplankton present different characteristics compared to other channels and fjords in the area, being mainly represented by small size species with low biomass values (Paredes 2005, Avaria et al. 1997). Its composition seems to be affected mainly by water temperature and nutrient concentrations (Avaria et al. 1997). Nonetheless, chlorophyll and size diversity is often modulated by a dynamic combination of several environmental variables (Paredes 2005). The Aysén Fjord present low biodiversity values, with a small increase near the head, where freshwater species like *Rhizosolenia eriensis* and *Melosira pseudogranulata* can be found (Avaria et al. 1999). In general, there is a good relationship between biomass (measured as chlorophyll a), cell density (Avaria et al. 1997) and size diversity (Paredes 2005) in the fjord's head. This suggests that most cells are photosintetically active and most species have similar size (Paredes 2005).

Phytoplankton communities are dominated through the year by microphytoplankton (20 to 200 μm), specially *Skeletonema costatum*, a small diatom with high growth rates attaining high densities during spring season (Avaria et al. 1997, 1999, 2004). After the spring maximum, diatoms abundance suffer a reduction during summer and winter, with smaller phytoplankton species [nano (2-20 μm) and picoplankton (0.2-2 μm)] increase their contribution. This cause the winter reduction of chlorophyll biomass, reaching values almost 10 times lower than spring (Fig. 2). Accordingly, as primary production is determined by the biomass and size structures of phytoplankton in southern fjords, productivity rates also follow this trend, with spring values even 10 times higher than winter (Pizarro et al. 2005a).

The region shows strong seasonal variations in the light climate Daily mean surface values of photosynthetically active radiation (PAR) in Aysén spring season reach 473 μM m^{-2} s^{-1} ($\approx$112.62 W m^{-2} according Lüning 1981), with a 19 m deep euphotic zone at the mouth and 10 m at the head. Summer values are close to 405 405 μM m^{-2} s^{-1} ($\approx$96.43 W m^{-2}) with a euphotic zone of 21 m at the fjord body (Pizarro et al. 2005a). Phytoplankton biomass influence over the optical conditions of the fjord waters could be larger in spring season, when biomass values reach 9.9 mg Chla m^{-2} integrated up to 50 m and with a euphotic zone 28 m deep at the fjord head, and the greater transparency of the water in summer, towards the interior of the fiord reflects already mentioned diminution of the biomass of the phytoplankton (Pizarro et al. 2005b). Moreover, the winter chlorophyll values decrease to 1.6-1.9 mg Chla m^{-2} integrated up to 50 m at the fjord mouth and to 3.5 mg Chla m^{-2} at the head, but the euphotic zone increases (i.e. 46 m at the fjord mouth).

Phytoplankton biomass variability is also explained by the intensity of herbivorous micro zooplankton grazing, which is dominated by copepods and crustaceous larvae, been abundant especially during summer and spring seasons (Avaria et al. 1999). The information about zooplankton in the Aysén Fjord is scanty, with studies focused only in one taxonomic group at a time, without ecosystemic or trophic considerations. Most of the time considering the presence, abundance and distribution of crustaceous larvae (Zama and Cárdenas 1984, Mujica and Medina 1997, Mujica 2003), fisheries (Pequeño 1981, Balbontín and Bernal 1997, 1999), mollusks (Vega et al. 2000) and gelatinous zooplankton (Palma y Rosales 1997, Palma and Aravena 2002). In general, all taxa show low diversity, which is explained by large salinity variations through the water column and high stratification, producing physical barriers on the daily vertical migration of larvae in feeding and anti-predatory behavior. Therefore, species found in the inner parts of the fjord must be adapted to this estuarine environment (Balbontín and Bernal 1997, Palma and Aravena 2002). The most abundant and widely distributed crustaceous decapods larvae belong to the infraorder Brachyura. Another important member of zooplankton communitiy is *Munida subrrugosa* (Mujica and Medina 1997, Mujica 2003), a small galatheid crab founded in large stocks that is an important source of food to marine invertebrates (Mattehews 1932).

Within zooplankton carnivorous, the greater predators of the copepods are quetognats (Alvariño 1985, Stuart and Verheye 1991, Casanova 1999), Aysén Fjord shows large densities but low species richness of quetognats during the summer and spring season, mainly influenced by salinity and temperature (Palma and Rosales 1995). The species of quetognats presents agree with the description their description of organisms strongly influenced by the salinity and the water temperature (Gasca et al. 1996, Marazzo and Nogueira 1996). Aditionally, Aysén Fjord's head has been pointed out as an important reproductive zone for southern fisheries in summer, with lower significance in spring season). Nevertheless fish larvae diversity is bigger than other taxa (Balbontín and Bernal 1999). Microbiological studies on the fjord's waters have focused on bacteria and fungi identification, especially those involved on the nitrogen cycle (Aguilera et al. 2002).
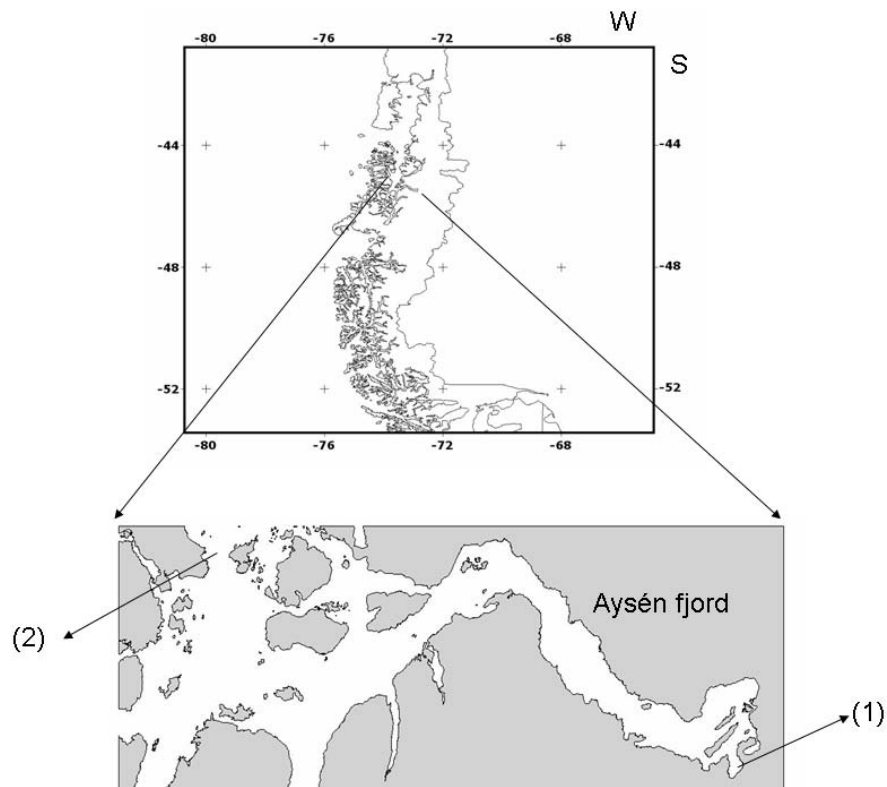
FIGURE 1: *Map of the Chile Southern Coastline, with details for the Aysen Fjord (lower map). (1) Chacabuco bay, (2) Constricción de Meninea.*
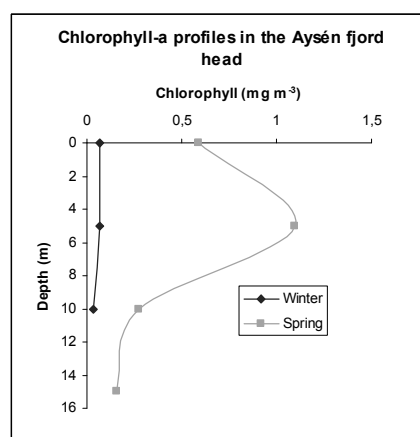

FIGURE 2: *Chlorophyll profiles of the Aysén fjord.*

The main results of these studies show bacteria getting maximum values during spring season, with values almost 100 times larger than winter concentrations for some functional groups. Samples also show that the area of the Fjord's head presents higher bacteria concentrations for almost every functional group -of the nitrogen cycle- compared with the oceanic area (Aguilera et al. 2002).

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